Static and Dynamic Mechanical Properties of Sustainable Engineered Geopolymer Composites

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Doctor of Philosophy in Civil Engineering
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Abstract

Engineered geopolymer composites (EGCs) exhibiting superior tensile strain-hardening and multiple cracking behaviour are sustainable alternatives to traditional ductile cementitious composites whereas the extremely high cost and potential environmental impact of the widely used oil-coated polyvinyl alcohol (PVA) or polyethylene fibres in EGCs would limit their large-scale application. Partial replacement of these fibres with recycled fibres can reduce the material cost and improve the sustainability of EGCs. In recent years, the fresh properties and static mechanical properties of EGCs made from different precursors including fly ash and ground granulated blast-furnace slag have been increasingly studied, while the dynamic mechanical properties of EGCs cured at ambient temperature have been rarely explored.

This thesis aims to develop a novel sustainable fly ash-slag based EGC with recycled tyre polymer (RTP) fibre as partial substitute for PVA fibre based on micromechanics design theory and systematically investigate the effect of hybrid PVA and RTP fibre content on the quasi-static and dynamic mechanical properties of EGCs. Firstly, a series of tests were conducted to study the engineering properties of EGCs with different PVA and RTP fibre dosages including workability, setting time, drying shrinkage, compressive strength, elastic modulus, splitting tensile strength, uniaxial tensile behaviour as well as the micromechanical characteristics in terms of fibre bridging stress-crack opening and strain-hardening indices. Afterwards, the dynamic compressive and splitting tensile behaviour were explored using the split Hopkinson pressure bar apparatus in terms of failure pattern, stress-strain (or displacement) response, dynamic compressive and splitting tensile strengths, dynamic increase factor (DIF) and energy absorption capacity. Some empirical equations were proposed to estimate the relationships between DIF and strain rate. Afterwards, the microstructural characterisation using scanning electron microscopy (SEM), backscattered electron microscopy (BSE) and X-ray computed tomography (XCT) techniques was carried out to understand the fibre bridging mechanism of the hybrid PVA-RTP fibre reinforced EGC. Lastly, the optimal mixtures of EGC were proposed considering the material cost, environmental impact, and acceptable engineering properties for civil infrastructure applications.
Results indicate that the developed EGCs can meet the strength-based and energy-based criteria for robust tensile strain-hardening behaviour. Replacing a small amount of PVA fibre with RTP fibre can lead to better dynamic mechanical properties and drying shrinkage resistance, lower material cost and higher sustainability as well as retaining acceptable static mechanical properties. This thesis can provide new insights into the effect of hybrid fibre reinforcement on the dynamic mechanical behaviour of EGCs under a wide range of strain rates ($10^0$ s$^{-1}$ to $10^3$ s$^{-1}$) as well as promote the development and application of low-carbon construction materials in the future.
Impact statement

Engineered geopolymer composites (EGCs) possessing superior tensile ductility are promising alternatives to their cement-based counterparts because of the lower carbon footprint and reduced energy consumption. Nevertheless, the material cost and potential environmental impact of the commonly used hydrophilic polyvinyl alcohol (PVA) or hydrophobic polyethylene (PE) fibres in EGCs would limit their large-scale application. Besides, the lack of understanding of the dynamic mechanical properties of EGCs would hinder their widespread application. Partial replacement of PVA or PE fibres with recycled fibres is a potential approach to reduce the material cost and improve the sustainability of EGCs. Therefore, the main aim of this research is to develop a novel sustainable fly ash-slag based EGC with hybrid PVA and recycled tyre polymer (RTP) fibres.

From the academic perspective, this research fills some critical gaps in this field. The effects of various PVA and RTP fibre dosages on the engineering properties, material cost and sustainability were systematically explored, enabling us to obtain the optimal mixtures that can achieve the desired performance. This study can provide a thorough understanding of the PVA and RTP fibre effects on the uniaxial tensile behaviour especially the strain-hardening behaviour of EGCs. Furthermore, some new insights about the effect of fibre content on the dynamic mechanical properties of EGCs under a wide range of strain rates are obtained from this study. Some proposed equations describing the relationship between DIF and strain rate can offer guidance for future structural design and numerical simulations.

From the industrial perspective, this research is beneficial to the development and application of sustainable construction materials in the future to help achieve net zero emissions by 2050. The proposed hybrid fibre reinforced EGCs in this thesis are promising sustainable alternatives to cement-based ductile composites containing either PVA or PE fibres and can be regarded as a good example of adopting industrial by-products and recycled tyre materials as secondary resources in construction materials. The optimal EGC mix proportion proposed in this study has great potential to be the construction material for 3D printing to improve construction efficiency and reduce the environmental impact caused by traditional mould-casting work. Additionally, it is highly promising to be used in various engineering applications, e.g., the repair and retrofitting of concrete structures.
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<th>Description</th>
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<tbody>
<tr>
<td>ATR-FTIR</td>
<td>Attenuated total reflectance Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>Agg/b</td>
<td>Aggregate-to-binder ratio</td>
</tr>
<tr>
<td>Add/b</td>
<td>Additive-to-binder ratio</td>
</tr>
<tr>
<td>BSE</td>
<td>Backscattered electron microscopy</td>
</tr>
<tr>
<td>C-A-S-H</td>
<td>Calcium aluminosilicate hydrate</td>
</tr>
<tr>
<td>ECC</td>
<td>Engineered cementitious composite</td>
</tr>
<tr>
<td>EGC</td>
<td>Engineered geopolymer composite</td>
</tr>
<tr>
<td>DIF</td>
<td>Dynamic increase factor</td>
</tr>
<tr>
<td>DSC</td>
<td>Differential scanning calorimetry</td>
</tr>
<tr>
<td>FRC</td>
<td>Fibre reinforced concrete</td>
</tr>
<tr>
<td>FA</td>
<td>Fly ash</td>
</tr>
<tr>
<td>GGBS</td>
<td>Ground granulated blast-furnace slag</td>
</tr>
<tr>
<td>GFS</td>
<td>Gypsum free slag</td>
</tr>
<tr>
<td>IFA</td>
<td>Incineration fly ash</td>
</tr>
<tr>
<td>LS</td>
<td>Ladle slag</td>
</tr>
<tr>
<td>LCDG</td>
<td>Liquid crystal display glass</td>
</tr>
<tr>
<td>L/b</td>
<td>Liquid-to-binder ratio</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear variable displacement transducer</td>
</tr>
<tr>
<td>MK</td>
<td>Metakaolin</td>
</tr>
<tr>
<td>MWCNT</td>
<td>Multi-walled carbon nanotube</td>
</tr>
<tr>
<td>N-A-S-H</td>
<td>Alkali aluminosilicate</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyvinyl alcohol</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene terephthalate</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>POFA</td>
<td>Palm oil fuel ash</td>
</tr>
<tr>
<td>RTP</td>
<td>Recycled tyre polymer</td>
</tr>
<tr>
<td>RTS</td>
<td>Recycled tyre steel</td>
</tr>
<tr>
<td>RM</td>
<td>Red mud</td>
</tr>
<tr>
<td>RHA</td>
<td>Rice husk ash</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>SF</td>
<td>Silica fume</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>SS</td>
<td>Steel slag</td>
</tr>
<tr>
<td>SP</td>
<td>Superplasticiser</td>
</tr>
<tr>
<td>SHPB</td>
<td>Split Hopkinson pressure bar</td>
</tr>
<tr>
<td>TGA</td>
<td>Thermogravimetric analysis</td>
</tr>
<tr>
<td>VMA</td>
<td>Viscosity modifying admixture</td>
</tr>
<tr>
<td>W/b</td>
<td>Water-to-binder ratio</td>
</tr>
<tr>
<td>W/s</td>
<td>Water-to-solid ratio</td>
</tr>
<tr>
<td>XCT</td>
<td>X-ray computed tomography</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
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</table>
List of Symbols

\( A_b \)  Cross-sectional area of the SHPB bar (mm\(^2\))
\( A_s \)  Cross-sectional area of the test sample (mm\(^2\))
\( C_b \)  Longitudinal wave velocity of the SHPB bar (ms\(^{-1}\))
\( d_f \)  Diameter of fibre (µm)
\( E_m \)  Elastic modulus of the matrix (GPa)
\( E_f \)  Elastic modulus of fibre (GPa)
\( E_s \)  Elastic modulus of the test sample (GPa)
\( E_b \)  Elastic modulus of the SHPB bar (GPa)
\( F_{pa} \)  Maximum force when debonding length equals the embedment length of fibre (N)
\( F_{pb} \)  Force at the start of fibre sliding (N)
\( F_p \)  Maximum load recorded during the three-point bending test (N)
\( F_{dt}(t) \)  History of dynamic splitting tensile force acting on the test sample (N)
\( f_c \)  Compressive strength of the test sample (MPa)
\( f_{st} \)  Splitting tensile strength of the test sample (MPa)
\( f_{dt} \)  Dynamic splitting tensile strength of the test sample (MPa)
\( G_d \)  Chemical bond (Jm\(^{-2}\))
\( h_s \)  Height of the test sample (mm)
\( J_{tip} \)  Crack tip toughness (Jm\(^{-2}\))
\( J'_b \)  Maximum complementary energy (Jm\(^{-2}\))
\( K_m \)  Fracture toughness of the matrix (MPa·m\(^{1/2}\))
\( L_f \)  Length of fibre (mm)
\( L_e \)  Embedment length of fibre (mm)
\( L_s \)  Length of the test sample (mm)
\( m_s \)  Mass of the test sample (kg)
\( n \)  Total number of adopted images
\( \rho_s \)  Density of the test sample (kgm\(^{-3}\))
\( S' \)  Sliding displacement (mm)
\( S \)  Loading span for the three-point bending test (mm)
\( t_s \)  Thickness of the test sample (mm)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$t_0$</td>
<td>Required time to achieve the peak of the transmission stress (µs)</td>
</tr>
<tr>
<td>$u(t)$</td>
<td>Relative displacement history of the two ends of the test sample along the loading direction (mm)</td>
</tr>
<tr>
<td>$W_{dt}$</td>
<td>Energy absorption capacity under dynamic splitting tension (J)</td>
</tr>
<tr>
<td>$\bar{x}$</td>
<td>Average number of fibres in all images</td>
</tr>
<tr>
<td>$x_i$</td>
<td>Number of fibres in the $i$-th image</td>
</tr>
<tr>
<td>$\sigma_{fc}$</td>
<td>Required stress to initiate the first crack (MPa)</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>Required stress to form another crack (MPa)</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>Maximum fibre bridging stress (MPa)</td>
</tr>
<tr>
<td>$\sigma_{ss}$</td>
<td>Steady-state bridging stress (MPa)</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>Stress at a longitudinal strain of 50 µε (MPa)</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>Stress corresponding to 40% of the ultimate stress (MPa)</td>
</tr>
<tr>
<td>$\sigma(t)$</td>
<td>Dynamic stress history (MPa)</td>
</tr>
<tr>
<td>$\sigma_{dt}(t)$</td>
<td>Dynamic splitting tensile stress history (MPa)</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>Longitudinal strain at $\sigma_2$</td>
</tr>
<tr>
<td>$\varepsilon_i(t)$</td>
<td>Incident pulse</td>
</tr>
<tr>
<td>$\varepsilon_r(t)$</td>
<td>Reflected pulse</td>
</tr>
<tr>
<td>$\varepsilon_t(t)$</td>
<td>Transmission pulse</td>
</tr>
<tr>
<td>$\varepsilon(t)$</td>
<td>Dynamic strain history</td>
</tr>
<tr>
<td>$\dot{\varepsilon}(t)$</td>
<td>Dynamic strain rate history</td>
</tr>
<tr>
<td>$\delta_0$</td>
<td>Crack opening corresponding to maximum fibre bridging stress (mm)</td>
</tr>
<tr>
<td>$\delta_{ss}$</td>
<td>Crack opening corresponding to steady-state bridging stress (mm)</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>Frictional bond (MPa)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Slip-hardening coefficient</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Fibre inclination angle (º)</td>
</tr>
<tr>
<td>$a_0$</td>
<td>Depth of the notch (mm)</td>
</tr>
<tr>
<td>$\alpha_f$</td>
<td>Fibre distribution coefficient</td>
</tr>
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Chapter 1 Introduction

1.1 Research background

Concrete is the most widely used construction material in the world, which is strong in compression but weak in tension with tensile strain capacity of only about 0.01% (Li, 2019). To suppress this weakness, an increasing number of studies have focused on the development of fibre reinforced cementitious composites since the 1960s (Naaman, 2007). However, as seen in Figure 1-1, ordinary fibre reinforced concrete (FRC) can lead to higher tensile strength than normal concrete but insufficient enhancement in tensile strain capacity. To achieve superior tensile ductility, engineered cementitious composites (ECCs) were developed in the early 1990s, featuring strain-hardening and multiple cracking behaviour (Li, 2019). Unlike normal concrete and normal FRC, ECCs strain-harden after the formation of the first crack and have tensile strain capacity of several hundred times higher than normal concrete and FRC. ECCs exhibit self-controlled crack widths under a loading state, where the initial cracks stop widening after exceeding about 1% tensile strain and the further tensile deformation is induced by the generation of new micro-cracks (Şahmaran and Li, 2009). Because of these unique characteristics, ECCs have been applied in various full-scale structures such as bridges and high-rise buildings to prolong the service life and offer improved functions (Maruta, 2005, Luković et al., 2019, Li et al., 2020a).

Figure 1-1 Typical tensile stress-strain curves of ECC, FRC and normal concrete (Şahmaran and Li, 2009, Li, 2008).

The typical ECCs are made from Portland cement, supplementary cementitious materials (e.g., fly ash (FA)), silica sand and short fibres, which contain about 2-3
times higher cement content than ordinary concrete due to the absence of coarse aggregates (Wang and Li, 2007). The production of Portland cement accounts for around 8% of the global CO₂ emissions (Luukkonen et al., 2018), implying that the increasing development of ECCs would hinder the sustainable development of construction industry. Therefore, it is vital to find alternative green binders for ECCs. In recent years, geopolymers (also called alkali-activated materials) made from aluminosilicate source materials and alkaline activators were utilised as binders to develop engineered geopolymer composites (EGCs) that are considered as promising substitutes for ECCs. Compared to normal Portland cement concrete, geopolymer concrete can achieve comparable or even more superior mechanical properties and durability as well as around 50-80% less CO₂ emissions (Yang et al., 2013, Provis, 2017). In comparison with ECCs, the developed EGCs are more sustainable and have similar tensile and flexural properties under static loading but better mechanical properties under dynamic loading (Shaikh, 2013, Nematollahi et al., 2017e, Cai et al., 2021, Trindade et al., 2020).

Up to now, different types of EGCs have been developed with various precursors, alkaline activators, aggregates and fibres. Among them, FA, ground granulated blast-furnace slag (GGBS) and their blends are the commonly used precursors for EGCs due to their large quantities around the world and relatively stable chemical components (Zhang et al., 2021, Duxson et al., 2007). Recently, EGCs made of blended FA and GGBS have received increasing attention as they can not only overcome some limitations existing in FA-based EGCs (e.g., requirement of heat curing for early strength) and GGBS-based EGCs (e.g., low workability, rapid setting and high shrinkage) but can also possess superior engineering properties under ambient temperature (Nematollahi et al., 2017e, Wang et al., 2020, Wang et al., 2021b, Nematollahi et al., 2017d, Zhang et al., 2020c). Similar to ECCs, hydrophilic polyvinyl alcohol (PVA) fibres with oil coating are mainly used at a fibre volume fraction of no higher than 2.0% to achieve the desired ductility for EGCs (Nematollahi et al., 2014, Nguyễn et al., 2021). Hydrophobic polyethylene (PE) fibres with a tensile strength of 2700-3500 MPa are also adopted as reinforcement to develop EGCs that have high strength and superior ductility (Nematollahi et al., 2017d, Zhao et al., 2021b, Lee et al., 2017). Nevertheless, the exceptionally high costs and inevitable environmental impacts during the production of these fibres would impede the large-scale application and sustainable development of EGCs (Zhang et al., 2020b, Yu and Leung, 2017, Merli...
et al., 2019). For instance, it was reported that the material cost and embodied energy of the ECC containing 2.0% (by volume) PVA fibre were 7.6 and 1.5 times higher compared to those of commercial Grade 45 concrete (Yu et al., 2018). To address these issues, an increasing number of studies have focused on the use of recycled fibres from wastes to replace PVA fibres in either ECCs or EGCs, which can not only improve the cost-effectiveness and sustainability of ECCs or EGCs but also reduce the amount of solid wastes. It was found that using recycled polyethylene terephthalate (PET) fibres from waste plastic bottles to replace 50% of PVA fibre in the ECC can reduce the material cost and embodied energy by around 20-40% without obviously weakening the uniaxial tensile behaviour especially strain-hardening and multiple cracking behaviour (Yu et al., 2018). In addition, the ECC with hybrid PVA and recycled PET fibres can exhibit excellent impact resistance with adequate tensile performance (Lu et al., 2018b). Recycled tyre steel (RTS) fibres from waste tyres have recently been adopted as the partial replacement of PVA fibres in EGCs (Wang et al., 2020).

It was reported that approximately 1500 million end-of-life tyres are created yearly (Malarvizhi et al., 2012). The enormous amount of these waste tyres would induce several environmental problems and increase the burden on landfilled areas (Thomas and Gupta, 2016). The end-of-life tyres can be used as the fuel source in cement kilns and the production of steam, electrical energy, paper, lime and steel (Ramarad et al., 2015, Fiksel et al., 2011, Amari et al., 1999). Additionally, several materials such as crumb rubber and RTS fibres can be retrieved from the waste tyres through mechanical shredding of tyres under ambient temperature, cryogenic degradation of tyres and also thermal degradation of tyres (e.g., pyrolysis) (Pilakoutas et al., 2004, Ramarad et al., 2015). It is worth noting that the mechanical shredding of tyres under ambient temperature is regarded as a commercially mature and technologically reliable process (Pilakoutas et al., 2004). A whole tyre is firstly shredded into pieces using a double-shaft grinder (Gigli et al., 2019) and the pieces are then fed into a second shredder to further reduce their sizes (Pilakoutas et al., 2004). Afterwards, magnets are adopted to separate the steel from the rubber and some textile fibres are collected using an air separator (Gigli et al., 2019, Onuaguluchi and Banthia, 2019). RTS fibres were found to be favourable for the improvements in drying shrinkage resistance and compressive strength of EGCs although the flexural strengths were weakened (Wang et al., 2020).

Recently, a growing emphasis has been placed on the use of another recycled tyre material, recycled tyre polymer (RTP) fibre, in cementitious materials as fibre
reinforcement. The motivation of introducing RTP fibres in the construction industry is to find a possible usage for them, as storing RTP fibres is a big challenge that may lead to several environmental problems (Baričević et al., 2018). The existing studies on the effect of RTP fibres in cementitious composites found that the presence of RTP fibres can improve the resistance of the resultant composites to fire spalling (Huang et al., 2015), autogenous, plastic and drying shrinkage cracking (Serdar et al., 2015, Onuaguluchi and Banthia, 2017, Chen et al., 2021a), and freeze-thaw cycles (Baričević et al., 2018, Baricevic et al., 2018), and enhance their dynamic properties and fatigue behaviour (Chen et al., 2019, Chen et al., 2020b, Chen et al., 2020a). Although RTP fibres in cementitious composites have several positive effects, the feasibility of using RTP fibres in geopolymers has not been extensively studied. From the economic and environmental perspectives, it is promising to develop a cost-effective and sustainable EGC with acceptable engineering properties through the replacement of commonly used PVA fibres with RTP fibres. To verify this hypothesis, it is vital to explore the effect of RTP fibres on the engineering properties and sustainability of EGCs made from FA and GGBS, which has not been addressed elsewhere.

The fresh properties and static mechanical properties of EGCs made from different precursors have been increasingly studied in recent years, while the dynamic mechanical properties of EGCs cured at ambient temperature have been rarely explored. Independent of the curing regime (ambient or heat curing), the tensile strength of all EGC mixtures under dynamic loading was higher than that under quasi-static loading, and all heat-cured EGCs exhibited ductile failure modes, although heat curing impaired the compressive and tensile strengths of EGCs (Farooq et al., 2022). Moreover, FA-GGBS based EGCs outperformed FA-based and GGBS-based EGCs in terms of quasi-static and dynamic tensile properties. In comparison with the PVA fibre reinforced EGC, the PE fibre reinforced EGC yielded better dynamic tensile strain capacity, dynamic bond strength and energy absorption capacity (Trindade et al., 2020). Besides, it had better dynamic tensile performance than the ECC reinforced with the same fibre because of the comparable matrix stiffness and crack-bridging stiffness. EGCs were found to have a comparable or better impact resistance than ECCs at both ambient temperature and elevated temperature (50-150 °C), and the impact resistance of the EGC was improved with the increasing molarity of sodium hydroxide up to 12 M (Cai et al., 2022). It was indicated that the dynamic mechanical behaviour of EGCs was sensitive to strain rate while only limited strain rates including 0.51 s\(^{-1}\) (Farooq et
al., 2022) and 300-330 s\(^{-1}\) (Trindade et al., 2020) were considered in the existing studies, which is not sufficient to understand their tensile performance when subjected to various dynamic loadings. Moreover, the effects of both PVA and RTP fibre dosages on the dynamic mechanical properties of EGCs are still not clear. To further understand the potential use of EGCs for concrete structures that may be subjected to various dynamic loadings, it is essential to comprehensively investigate the effects of various strain rates, PVA fibre contents and RTP fibre contents on the dynamic mechanical properties, especially compressive and tensile behaviour of EGCs. In summary, the following aspects about FA-GGBS based EGCs are still inadequate:

- Feasibility of partially replacing PVA fibres with RTP fibres in EGCs considering the basic engineering properties such as workability and compressive strength.
- Effects of various PVA and RTP fibre dosages on uniaxial tensile behaviour of EGCs.
- Experimental estimation of dynamic mechanical properties of EGCs accounting for the effects of strain rates (10\(^0\) to 10\(^3\) s\(^{-1}\)) and fibres (PVA and RTP).

Therefore, given the lack of understanding in the above fields, the aim, objectives and strategy of this research are given below.

1.2 Aim, objectives and scope of this research

The overall aim of this research is to develop a sustainable hybrid fibre reinforced cement-free EGC with acceptable engineering properties, superior tensile ductility and dynamic mechanical properties, and lower material cost and carbon footprint. The results of this research can help promote the sustainable development of construction industry by utilising industrial by-products and recycled tyre materials as main constituents. In addition, the superior dynamic mechanical properties of proposed materials can help prolong the service life of concrete structures with increased safety and resilience, especially when the structures are under extreme loading conditions.

The specific objectives to achieve the overall aim of this research are listed as follows:

- To explore the effects of different PVA and RTP fibre dosages on the basic engineering properties of EGCs including workability, setting time, drying shrinkage, compressive strength, elastic modulus and splitting tensile strength.
- To characterise the uniaxial tensile behaviour of EGCs with various PVA and RTP fibre dosages and verify whether the proposed mixes can achieve the robust
tensile strain-hardening behaviour based on micromechanics design theory. The fibre bridging mechanism of proposed EGC mixes will be explored using scanning electron microscopy (SEM), backscattered electron microscopy (BSE) and X-ray computed tomography (XCT) techniques.

- To study the effects of strain rate and fibre on the dynamic compressive behaviour of EGCs in terms of failure mode, stress-strain response, dynamic compressive strength, dynamic increase factor (DIF), and energy absorption capacity, as well as the underlying mechanisms.
- To investigate the effects of strain rate and fibre on the dynamic splitting tensile behaviour of EGCs including failure pattern, stress-displacement response, dynamic splitting tensile strength, DIF, and energy absorption capacity, as well as the underlying mechanisms.

1.3 Research strategy

To achieve the above objectives, the strategies adopted are given as follows:

- The as-received RTP fibres normally contain a large number of rubber particles, which may affect the hardened properties of EGCs. Therefore, a cleaning process is conducted to remove most of the impurities and rubber particles. Additionally, the primary composition and main properties of RTP fibres are characterised prior to the experimental work.
- A series of tests including workability, setting time, drying shrinkage, compressive strength, elastic modulus and splitting tensile strength tests are performed to characterise the basic engineering properties of EGCs with different PVA and RTP fibre contents. The data of elastic modulus and splitting tensile strength is compared with the existing prediction models. The material cost, embodied carbon and embodied energy of studied mixes are estimated and compared with those of the commonly used ECCs.
- Uniaxial tensile tests are carried out to explore the effects of PVA and RTP fibres on the tensile behaviour of EGCs. In particular, the stress-strain response, first cracking strength, tensile strength, tensile strain capacity, tensile strain energy, and cracking pattern are analysed. The tensile strain-hardening behaviour of all investigated mixtures is verified using two strain-hardening indices that are obtained by conducting the single crack direct tension and fracture toughness tests. The fibre status after the uniaxial tensile test is characterised using a
portable digital microscope and SEM equipment, which is used to further understand the fibre bridging mechanism. The pore structure and fibre distribution of mono-PVA fibre reinforced and hybrid fibre reinforced EGCs are studied using the XCT and BSE techniques, which can provide insights into their relations with mechanical properties.

- Based on the experimental results obtained above, the optimal mixtures of hybrid fibre reinforced EGC are evaluated to achieve the desired performance in terms of acceptable engineering properties, superior tensile ductility, lower material cost and higher sustainability.

- To study the dynamic mechanical properties of EGCs, a split Hopkinson pressure bar (SHPB) apparatus is adopted, which has been often utilised to explore the behaviour of concrete under a wide range of high strain rates \(10^0 \text{ s}^{-1} \text{ to } 10^3 \text{ s}^{-1}\). In total, 168 test samples are prepared and used for SHPB tests. Preliminary tests are performed to select the dimension of the pulse shaper that can help achieve the dynamic stress equilibrium during the SHPB test. Based on the obtained experimental data, some empirical equations describing the relationships between DIF and strain rate are proposed, which are helpful for future predictions. The fibre condition after dynamic loadings is investigated using a portable digital microscope and SEM test.

1.4 Thesis outline

This thesis consists of the following seven chapters (see Figure 1-2).

**Chapter 1** introduces the research background, aim and objectives as well as the adopted research strategy.

**Chapter 2** presents a critical state-of-the-art review of EGCs mainly covering compositional materials, fabrication process, design theory, engineering properties and durability. The main challenges and limitations existing in this field are also identified and discussed.

**Chapter 3** illustrates an experimental characterisation of the basic engineering properties of FA-GGBS based EGCs cured at ambient temperature with different PVA and RTP fibre dosages. The properties of adopted raw materials are provided as well as the description of each test method. Besides, the environmental impact and material cost of all studied mixtures are analysed and discussed in depth.
Chapter 4 demonstrates an experimental study on the uniaxial tensile behaviour of FA-GGBS based EGCs incorporating various PVA and RTP fibre contents. The tensile stress-strain response, first cracking strength, tensile strength, tensile strain capacity, tensile strain energy and cracking behaviour of studied EGC mixes are discussed in detail. The micromechanical and microstructural investigations are presented as well to understand the microstructure-tensile property relationships in EGCs.

Chapter 5 displays the experimental process of the dynamic compressive test and the corresponding results. The effects of different PVA and RTP fibre dosages on the dynamic stress-strain response, failure pattern, dynamic compressive strength, DIF and energy absorption capacity of EGCs are discussed.

Chapter 6 illustrates the test method of the dynamic splitting tensile test and the corresponding results, focusing on the effect of PVA and RTP fibres on the dynamic stress-displacement response, failure pattern, dynamic splitting tensile strength, DIF and energy absorption capacity of EGCs.

Chapter 7 gives a summary of the main contributions of this research and the main conclusions of this thesis. In addition, the limitations of this research are mentioned, along with some recommendations for future research.
Chapter 2 Literature review

2.1 Introduction

This chapter presents a critical review of the state-of-the-art of EGCs in terms of mix design, fabrication process, design theory and engineering properties, with special focus on the effects of different material composition factors including precursor, activator, aggregate, additive and fibre on the critical material properties of EGCs especially uniaxial tensile properties. In addition, the correlations between essential material properties are discussed in depth. Lastly, the research gap and limitations in this field of research can be identified. It should be noted that part of this chapter has been presented in a peer-reviewed journal paper:

2.2 Composition and production of engineered geopolymer composites (EGCs)

2.2.1 Raw materials and mix design

Geopolymers are produced via the reaction between aluminosilicate raw materials (i.e., precursors) and alkaline activators, where their reaction process can be divided as (Provis and Bernal, 2014): (1) dissolution, (2) rearrangement, (3) gel nucleation, and (4) solidification. When the raw binder materials are in contact with the alkaline activator, the surface bonds of the binders (e.g., Si-O-Si and Al-O-Al bonds in FA, CaO and Si-O-Si bonds in GGBS) are ruptured to generate a variety of dissolved species (e.g., silica, alumina and calcium monomers) (Weng and Sagoe-Crentsil, 2007, Ranjbar et al., 2020). As the dissolution continues, these monomers would react with each other to form dimers, leading to the formation of 3D aluminosilicate gels. When a low-calcium precursor (e.g., FA) is used, the alkali aluminosilicate (N-A-S-H) gel is the main reaction product with a highly crosslinked disordered pseudo-zeolitic structure (Provis and S. J. van Deventer, 2014, Provis et al., 2005), while the mixture containing a high-calcium precursor (e.g., slag) would primarily consist of calcium aluminosilicate hydrate (C-A-S-H) gel with a tobermorite-like structure (Provis and S. J. van Deventer, 2014, Provis et al., 2015). These gels can coexist if the precursors are blends of low-calcium and high-calcium binders (Yip et al., 2005).

Table 2-1 summarises the used raw materials, mixture design and curing regime for fabricating EGCs. So far, different types of EGCs have been developed using various precursors, activators, aggregates and fibres. FA, GGBS and their blends were
the frequently used precursors owing to their large availability and relatively stable chemical compositions (Zhang et al., 2020c; Duxson et al., 2007). The commonly adopted contents of FA and GGBS were 50-80% and 20-50% (by the total mass of binders) for the blended FA and GGBS system. About 6-19% silica fume (SF) can be incorporated into GGBS or blended FA and GGBS systems to enhance the strength of EGCs as a result of its fine particle size and pozzolanic reaction (Khan and Siddique, 2011). Metakaolin (MK) was used alone or along with FA (1.5%) to improve the overall properties of EGCs because of its high active silica and alumina contents. Apart from the precursors above, ladle slag (LS) and steel slag (SS) from the steel-making process (Nguyen et al., 2018; Zhao et al., 2021b), palm oil fuel ash (POFA) from the palm oil industry (Salami et al., 2017; Salami et al., 2016), red mud (RM) generated during alumina extraction (Kan and Wang, 2022), incineration fly ash (IFA) from municipal solid waste incineration (Kan et al., 2020b), rice husk ash (RHA) created via burning rice husk (Yaswanth et al., 2022b; Yaswanth et al., 2022a), and liquid crystal display glass (LCDG) from the waste electronics (Yoo et al., 2022) were also utilised to produce EGCs for offering environmental benefits.

A combination of NaOH and Na$_2$SiO$_3$ was the most used liquid alkaline activator for EGCs because of the relatively good excitation effect (Duxson et al., 2005; Zhao et al., 2021a). The molarity of the used NaOH solution ranged from 4 M to 20 M, while the silicate modulus (SiO$_2$/Na$_2$O) of Na$_2$SiO$_3$ was in the range of 2.0-3.3. It should be mentioned that blending NaOH and Na$_2$SiO$_3$ solutions can release a large amount of heat, which requires a certain time to cool down before usage and is thereby time-consuming. Besides, it is not viable to handle a large quantity of corrosive alkaline solutions for large-scale applications. Hence, solid activators (e.g., anhydrous Na$_2$SiO$_3$) can be used instead, along with water during the mixing process, which can address some drawbacks of employing traditional liquid activators (Sturm et al., 2015). Most researchers have adopted liquid-to-binder ratios (L/b) ranging from 0.40 to 0.55 or water-to-solid ratios (W/s) of 0.20-0.35 for the mix designs of EGCs.

Similar to ECCs, silica sand with average particle size of 100-236 µm and maximum particle size of less than 1180 µm was generally used as fine aggregate for EGCs and coarse aggregate is inhibited as it can result in increased fracture toughness for the matrix ($K_m$) and therefore impair the unique tensile characteristics (i.e., strain-hardening and multiple cracking) of EGCs (Khan et al., 2016). To reduce the environmental impact induced by the overexploitation of natural resources and landfill
of solid wastes such as waste tyres (Thomas and Harilal, 2019, Thomas and Gupta, 2016), other types of aggregates including expanded glass, ceramic microsphere, expanded perlite, crumb rubber, and copper slag were employed to fully or partially replace the commonly used silica sand (Nematollahi et al., 2017c, Yaswanth et al., 2022a, Luong et al., 2021). The aggregate-to-binder ratio (Agg/b) was normally controlled for obtaining a suitable $K_m$ for the matrix and typically ranged from 0.2 to 0.5.

Different types of additives such as superplasticisers (SPs) and viscosity modifying admixtures were adopted to control the rheology of EGC’s matrix as it can strongly affect the fibre distribution and orientation (Wang et al., 2021a). Besides, defoamers or anti-foaming agents were used to reduce the formation of foam inside EGCs, which can change the internal pore structure, $K_m$ and interfacial properties between matrix and fibre (Lee et al., 2017). The contents of these additives were small, typically less than 1% of the total mass of the binder.

Like ECCs, EGCs contain randomly distributed short fibres at a dosage level of mostly no higher than 2.0%. PVA fibre is a kind of synthetic fibre that has been widely used as fibre reinforcement in EGCs due to its excellent mechanical properties, chemical resistance and easy dispersion (Shoji et al., 2022). Besides, as seen in Table 2-1, the diameter of the used PVA fibre is around 40 µm, which is small enough to improve the interfacial area between fibre and matrix for the desired ductility of EGCs (Shoji et al., 2022). Moreover, PVA fibre can have a strong bonding with the matrix due to the presence of hydroxyl groups in its molecular chains (Redon et al., 2001), which has a higher tendency to rupture during the fibre pull-out process and hence weaken the tensile ductility of the composites. Hence, oil coating is normally adopted on the surface of the PVA fibre for reducing the probability of fibre rupture and achieving superior tensile ductility (Qi et al., 2020). PE fibre with a hydrophobic surface feature was also often used to develop EGCs with both high tensile strength and ductility. It is worth noting that the tensile strength of PE fibre (2700-3500 MPa) is higher than that of PVA fibre. Apart from PVA and PE fibres, polypropylene (PP), glass and steel fibres, chopped steel wool and multi-walled carbon nanotube (MWCNT) were also used for EGCs. Although PVA and PE fibres are the most suitable reinforcements for EGCs, their exceptionally high costs and inevitable environmental impacts whilst the manufacture would result in lower cost-effectiveness and sustainability for EGCs (Merli et al., 2019, Zhang et al., 2020b). As a result, recycled
fibres from waste products such as RTS fibres have been employed to partially replace PVA fibres (Wang et al., 2020), which can not only be beneficial for the sustainability of EGCs but also contribute to the reduction of solid wastes (waste tyres).

2.2.2 Manufacturing process

In general, EGCs can be produced using either one-part or two-part mixing approach. Regarding the two-part mixing, the alkaline activator should be prepared separately before the mixing of the EGC. For instance, blending NaOH and Na$_2$SiO$_3$ requires about 24 h to allow heat dissipation. It starts with the mixing of dry materials including precursors and aggregates (if any), followed by the addition of activators, water and additives (if any). Once the mixture reaches a flowable and consistent state, the fibres are gradually added to ensure uniform fibre distribution while avoiding fibre-clumping and fibre-balling. For one-part mixing, solid-state activators are mixed with the precursors and aggregates, and the remaining procedure is similar to that of two-part mixing. To improve the dispersion of some fibres (e.g., MWCNT), they are first mixed with dispersant and water (Li et al., 2021a). It is worth noting that an effective dispersion of nanoparticles can be more conducive to improving the properties of the resultant composites (Luo et al., 2021). There is no specific total time duration for the mixing of EGCs as most studies used visual observation to define whether the consistent state of the paste (or mortar) samples was achieved. Regardless of the mixing approach, the total mixing time was in the range of 5-25 min.

The pouring method is the main approach to preparing EGC mixtures. As shown in Table 2-1, most FA-based EGC samples require heat curing (45-105 °C) to gain early-age strength while water curing at ambient temperature was typically adopted for GGBS-based EGCs. EGCs with a large proportion of GGBS may present poor workability, quick setting time and high shrinkage (Ye and Radlińska, 2016, Puertas et al., 2000, Fang and Zhang, 2020, Tang and Li, 2022), which may not be favourable for engineering applications. To address the drawbacks of FA- and GGBS-based EGCs, some researchers employed the blended FA and GGBS as the precursor of EGCs and found that they can achieve desirable fresh properties and comparable or even better hardened properties than that with FA or GGBS under ambient temperature curing (around 20 °C) (Zhang et al., 2020c, Farooq et al., 2022, Nematollahi et al., 2017e, Nematollahi et al., 2017d).
Table 2-1 Summary of raw materials, mix design and curing regime collected from studies on EGCs.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Binder (weight ratio)</th>
<th>Activator</th>
<th>L/b (or W/s or W/b)</th>
<th>Additive (Add/b)</th>
<th>Aggregate Type</th>
<th>Fibre Type (%) by volume</th>
<th>Type (L/b, mm/μm) [strength, MPa]</th>
<th>Curing regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee et al. (2012), Lee et al. (2017)</td>
<td>GGBS (1.0)</td>
<td>Ca(OH)₂ + Na₂SO₄, Ca(OH)₂ + Na₂SiO₃(2)²</td>
<td>W/s (0.30-0.438)</td>
<td>SP (0.0-0.03) + VMA (0, 0.0016) + antifoamer (0-0.002)</td>
<td>Silica sand (100)³</td>
<td>PVA (2.0), PE (1.75)</td>
<td>PVA (12/39) [1620], PE (18/12) [2700]</td>
<td>Water curing at 23 °C (26 d, 27 d)</td>
</tr>
<tr>
<td>Shaikh (2013)</td>
<td>FA (1.0)</td>
<td>NaOH (8) + Na₂SiO₃(2)²</td>
<td>L/b (0.45)</td>
<td>-</td>
<td>Sand (600, 1180)²</td>
<td>PVA (0.1, 2.0) + steel (0, 1.0, 2.0)</td>
<td>PVA (8/40) [1600], Steel (10/120) [2500]</td>
<td>65 °C (1 d) + air curing (27 d)</td>
</tr>
<tr>
<td>Ohno and Li (2014), Ohno and Li (2018)</td>
<td>FA (1.0)</td>
<td>NaOH + Na₂SiO₃ (3.2)³</td>
<td>L/b (0.4, 0.47)</td>
<td>-</td>
<td>Silica sand (110)²</td>
<td>PVA (1.0, 1.5, 2.0)</td>
<td>PVA (12/39) [1620]</td>
<td>Water curing at 23 °C (27 d)</td>
</tr>
<tr>
<td>Choi et al. (2015), Choi et al. (2019b)</td>
<td>GGBS (0.6) + Cement (0.4)</td>
<td>Ca(OH)₂ + Na₂SO₄</td>
<td>W/s (0.4)</td>
<td>SP + methyl cellulose + defoamer (0.003)</td>
<td>Silica sand</td>
<td>0.3, 0.4</td>
<td>PVA (1.0, 1.3), PE (1.5, 1.75, 2.0)</td>
<td>PVA (8/40) [1600], PE (18/12, 12/16, 12/32) [2700, 3030]</td>
</tr>
<tr>
<td>Nematiollahi et al. (2016), Nematiollahi et al. (2017d), Nematiollahi et al. (2017a), Nematiollahi et al. (2017e), Nematiollahi et al. (2017b), Nematiollahi et al. (2017c), Nematiollahi et al. (2014), Nematiollahi et al. (2015)</td>
<td>GGBS (0.5, 1.0) + GGS (0, 0.5) + GFS (0, 0.5)</td>
<td>NaOH (8)³ + Na₂SiO₄(2)³, KOH (8)³ + K₂SO₄(2.2)³, Ca(OH)₂ + Na₂SiO₃(2)³, NaOH (8)³, Na₂SiO₃ (anhydrous)</td>
<td>W/s (0.20, 0.23, 0.33), L/b (0.36, 0.45)</td>
<td>SP (0, 0.01)</td>
<td>Silica sand (165)³ (212, 1180)³</td>
<td>PVA (2.0), PE (2.0)</td>
<td>PVA (8/39, 8/40) [1600], PE (12/12) [3500]</td>
<td>Water curing at 23 °C (27 d), 60 °C (1 d) + air curing (2 d)</td>
</tr>
<tr>
<td>Salami et al. (2016), Salami et al. (2017)</td>
<td>POFA (1.0)</td>
<td>NaOH (8)³ + Na₂SiO₄(3.3)³</td>
<td>L/b (0.50-0.65)</td>
<td>SP (0, 0.05, 0.10)</td>
<td>Dune sand</td>
<td>1.8</td>
<td>PVA (2.0)</td>
<td>PVA (8/40) [1600]</td>
</tr>
<tr>
<td>Al-Majidi et al. (2017)</td>
<td>FA (0.5) + GGBS (0.4) + SF (0.1)</td>
<td>NaOH (8)³ + Na₂SiO₄(1.25)³</td>
<td>L/b (0.37)</td>
<td>-</td>
<td>Silica sand (500)³</td>
<td>1.36</td>
<td>PVA (1.0, 2.0), Glass (1.0), Hooked-end steel (0, 1.0) + straight steel (0-3.0)</td>
<td>PVA (12/15) [1560], Straight steel (6/160, 13/160) [2250], Hooked-end steel (50/1000) [1150], Glass (13/130) [1620]</td>
</tr>
<tr>
<td>Nguyen et al. (2018)</td>
<td>LS (1.0)</td>
<td>KOH (1)³ + Na₂SiO₄(3.5)³</td>
<td>L/b (0.7)</td>
<td>Borax (0.002)</td>
<td>Sand (1450)³</td>
<td>0.5</td>
<td>PP (2.0)</td>
<td>PP (12/20, 20/38) [220, 340]</td>
</tr>
<tr>
<td>Authors</td>
<td>Mix Design</td>
<td>Admixtures</td>
<td>Workability</td>
<td>Compressive Strength</td>
<td>Curing Method</td>
<td>Cure Age</td>
<td>Environment</td>
<td></td>
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<tr>
<td>Li et al. (2021a)</td>
<td>FA (0, 0.5) + GGBS (0.5, 1.0)</td>
<td>Na₂SiO₃ (anhydrous)</td>
<td>W/s (0.4)</td>
<td>-</td>
<td>Silica sand (212)³</td>
<td>0, 0.3</td>
<td>PE (0-2.0) + steel (0-2.0)</td>
<td>Water curing (27 d)</td>
</tr>
<tr>
<td>Nguyen et al. (2018), Nguyen et al. (2019a), Nguyen et al. (2019b)</td>
<td>FA (1.0)</td>
<td>NaOH (4-20) + Na₂SiO₃</td>
<td>W/s (0.23)</td>
<td>-</td>
<td>Silica sand (710)³</td>
<td>0.3</td>
<td>PVA (2.0)</td>
<td>Water curing at 23 °C (5 d, 26 d)</td>
</tr>
<tr>
<td>Zahid et al. (2018), Zahid et al. (2020)</td>
<td>FA (0, 0.4, 1.0) + GGBS (0, 0.6, 1.0)</td>
<td>NaOH (8, 12) + Na₂SiO₃</td>
<td>L/b (0.60, 0.61, 0.63)</td>
<td>-</td>
<td>River sand</td>
<td>0.5, 1.0</td>
<td>PVA (1.0, 2.0, 3.0), Steel (1.0, 2.0, 3.0), PP (2.0, 3.0), Chopped steel wool (2.0, 3.0)</td>
<td>30-105 °C (1 d) + air curing (27 d), 60 °C (28 d)</td>
</tr>
<tr>
<td>Farooq et al. (2019), Farooq et al. (2022)</td>
<td>FA (0.7-1.0) + GGBS (0-0.3)</td>
<td>NaOH + Na₂SiO₃ (2.7)³</td>
<td>L/b (0.27)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>PVA (2.0)</td>
<td>PVA (12/40) [1586]</td>
</tr>
<tr>
<td>Ling et al. (2019)</td>
<td>FA (0.7-1.0) + GGBS (0-0.3)</td>
<td>NaOH + Na₂SiO₃ (3.2, 3.3)³</td>
<td>L/b (0.53)</td>
<td>-</td>
<td>Silica sand (200)³</td>
<td>0.26, 0.3</td>
<td>PVA (2.0)</td>
<td>50 °C (3 d, 7 d, 28 d)</td>
</tr>
<tr>
<td>Kan et al. (2019), Kan et al. (2020a)</td>
<td>FA (0.97) + MK (0.03)</td>
<td>NaOH + Na₂SiO₃ (3.3)³</td>
<td>L/b (0.32)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>PVA (2.0)</td>
<td>PVA (8/40) [1640]</td>
</tr>
<tr>
<td>Zhang et al. (2020c)</td>
<td>FA (0.7) + GGBS (0.3)</td>
<td>NaOH + Na₂SiO₃ (3.3)³</td>
<td>W/b (0.32)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>PVA (2.0)</td>
<td>20 °C and ≥ 98% RH (28 d)</td>
</tr>
<tr>
<td>Kan et al. (2020c)</td>
<td>FA (0.91-1.0) + Zeolite (0-0.09)</td>
<td>NaOH + Na₂SiO₃ (3.3)³</td>
<td>L/b (0.55)</td>
<td>-</td>
<td>Silica sand</td>
<td>0.3</td>
<td>PVA</td>
<td>PVA (12/39) [1600]</td>
</tr>
<tr>
<td>Wang et al. (2020), Wang et al. (2021b)</td>
<td>FA (0.8) + GGBS (0.2)</td>
<td>NaOH (10)+ Na₂SiO₃ (2.0)³</td>
<td>L/b (0.4, 0.45)</td>
<td>SP (0.01)</td>
<td>Silica sand</td>
<td>1.0-0.4</td>
<td>PVA (1.5, 1.75, 2.0) + RTS (0, 0.25, 0.5)</td>
<td>PVA (12/40) [20850]</td>
</tr>
<tr>
<td>Kan et al. (2020b)</td>
<td>GGBS (0.32-0.81) + SF (0.08-0.19) + IFA (0-0.6)</td>
<td>NaOH + Na₂SiO₃ (3.2)³</td>
<td>L/b (0.53)</td>
<td>-</td>
<td>Sand</td>
<td>0.26</td>
<td>PE</td>
<td>PE (12/24) [3000]</td>
</tr>
<tr>
<td>Trindade et al. (2020), Constâncio Trindade et al. (2022)</td>
<td>FA + GGBS + SF + MK</td>
<td>Na-alkali-based solution, K-alkali-based solution</td>
<td>-</td>
<td>-</td>
<td>Quartz sand (200)³</td>
<td>0, 0.5</td>
<td>PVA (2.0)</td>
<td>PVA (12/40) [1600], PE (12/20) [2500]</td>
</tr>
<tr>
<td>Li et al. (2021a)</td>
<td>FA + GGBS + SF + MK</td>
<td>NaOH + Na₂SiO₃ (3)³</td>
<td>-</td>
<td>-</td>
<td>Silica sand</td>
<td>-</td>
<td>-</td>
<td>PVA (0.15, 0.2, 0.25) + MWCNT (0.05, 0.10, 0.15, by mass)</td>
</tr>
<tr>
<td>Authors</td>
<td>Composition</td>
<td>Water-Binder Ratio</td>
<td>Binder</td>
<td>Type</td>
<td>Maturity</td>
<td>Temperature</td>
<td></td>
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<tr>
<td>Zhao et al. (2021b)</td>
<td>FA (0.23-0.30) + GGBS (0.52-0.70) + SS (0.25)</td>
<td>L/b (0.52)</td>
<td>0.3</td>
<td>PE</td>
<td>PE (12/24) [3000]</td>
<td>100 °C (2 h) + air curing (28 d)</td>
<td></td>
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<td>Luong et al. (2021)</td>
<td>GGBS (0.94, 1.0) + SF (0.06)</td>
<td>SP (0.03-0.06)</td>
<td>Crumb rubber</td>
<td>PE (1.75)</td>
<td>PE (18/12) [2700]</td>
<td>Water curing at 23 °C (26 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kan et al. (2021)</td>
<td>FA (0.1) + GGBS (0.9)</td>
<td>L/b (0.54)</td>
<td>0.3</td>
<td>PE</td>
<td>PE (12/24) [3000]</td>
<td>80 °C (2 h) + 20 °C and 70% RH (0-119 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nguyen et al. (2021)</td>
<td>FA (1.0)</td>
<td>W/s (0.345)</td>
<td>-</td>
<td>PE</td>
<td>PE (18/12) [2700]</td>
<td>80 °C (1.5 d) + 23 °C (21.5 d)</td>
<td></td>
<td></td>
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<tr>
<td>Cai et al. (2021), Cai et al. (2022)</td>
<td>MK (1.0)</td>
<td>L/b (0.8)</td>
<td>0.4</td>
<td>PVA</td>
<td>PVA (12/26) [1560]</td>
<td>20 °C and 95% RH (28 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chan and Zhang (2022)</td>
<td>FA (0.8) + GGBS (0.2)</td>
<td>SP (0.01)</td>
<td>Silica sand</td>
<td>0.2</td>
<td>PVA (2.0)</td>
<td>20 °C and 95% RH (27 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kan and Wang (2022)</td>
<td>GGBS (0.73, 0.81) + SF (0.17, 0.19) + RM (0, 0.1)</td>
<td>L/b (0.53)</td>
<td>River sand</td>
<td>0.26</td>
<td>PE (1.9)</td>
<td>PE (12/24) [3000]</td>
<td>20 °C and 70% RH (27 d), 80 °C (2 h) + 20 °C and 70% RH (27 d)</td>
<td></td>
</tr>
<tr>
<td>Lao et al. (2022)</td>
<td>FA (0.2, 0.4, 0.55) + GGBS (0.37, 0.60, 0.80) + SF (0, 0.08)</td>
<td>W/s (0.2)</td>
<td>Borax (0.051)</td>
<td>Silica sand</td>
<td>PVA (2.0)</td>
<td>PVA (12/40) [1600]</td>
<td>20 °C and 95% RH (27 d)</td>
<td></td>
</tr>
<tr>
<td>Yaswanth et al. (2022b), Yaswanth et al. (2022a)</td>
<td>GGBS (0.97) + RHA (0.03)</td>
<td>W/s (0.3)</td>
<td>SP (0.07)</td>
<td>Silica sand, Silica sand + copper slag (2400)</td>
<td>2.25-2.70</td>
<td>PVA (2.0)</td>
<td>PVA (12/24) [1604]</td>
<td>Air curing at 25 °C (3-90 d)</td>
</tr>
<tr>
<td>Yoo et al. (2022)</td>
<td>GGBS (0.5) + LDCG (0.5)</td>
<td>W/b (0.35)</td>
<td>0-1.0</td>
<td>PE (2.0)</td>
<td>PE (12/20) [-]</td>
<td>Air curing (7 d) + water curing at 85 °C (1 d) + air curing (2 d) 25 °C and ≥ 80% RH (28 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kumar et al. (2022)</td>
<td>FA (0.5) + GGBS (0.5)</td>
<td>L/b (0.52)</td>
<td>0.3-1.0</td>
<td>PE (1.5) + steel (0.5)</td>
<td>PE (18/17) [3000], Steel (13/200) [2850]</td>
<td>70 °C (1 d) + air curing (28 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humur and Çevik (2022b, Humur and Çevik (2022a)</td>
<td>FA (0.0, 0.5, 1.0) + GGBS (0.5, 0.5, 1.0)</td>
<td>L/b (0.47)</td>
<td>Expanded glass</td>
<td>0.2</td>
<td>PVA (0, 1.0, 2.0) + PP (0, 1.0, 2.0)</td>
<td>PVA (12/39) [1620], PP (12/40) [450]</td>
<td>70 °C (1 d) + air curing (28 d)</td>
<td></td>
</tr>
</tbody>
</table>

Note: FA = fly ash, GGBS = ground granulated blast-furnace slag, SF = silica fume, MK = metakaolin, GFS = gypsum free slag, POFA = palm oil fuel ash, LS = ladle slag, SS = steel slag, IFA = incineration fly ash, RM = red mud, RHA = rice husk ash, LCDG = liquid crystal display glass, SP = superplasticiser; VMA = viscosity modifying admixture, PVA = polyvinyl alcohol, PE = polyethylene, PP = polypropylene, RTS = recycled tyre steel, MWCNT = multi-walled carbon nanotube, L/b = liquid-to-binder ratio (the mass ratio of total liquid over the mass of solid from the binder), W/s = water-to-solid ratio (the mass ratio of total water over the mass of solids from the binder and alkaline activator), W/b = water-to-binder ratio (the mass ratio of total water over the mass of solid from the binder), Add/b = additive-to-binder ratio, Agg/b = aggregate-to-binder ratio, L_f = length of fibre, d_f = diameter of fibre.

^ for molarity of sodium or potassium hydroxide solution, ^b for silicate modulus of sodium or potassium silicate solution, ^c for average particle size, ^d for maximum particle size, μm.
2.3 Micromechanical design theory of EGCs

2.3.1 Design theory

Unlike the design principle for high compressive strength in concrete (i.e., tight particle packing), the unique features of ECCs or EGCs are achieved using the micromechanics model that synergises the interaction between matrix, fibre, and fibre-matrix interface (Li, 2019). This design model is regarded as an effective tool to optimise the properties of ECCs or EGCs. To guarantee the strain-hardening and multiple cracking features for EGCs, two criteria including strength-based and energy-based must be satisfied. Figure 2-1 presents a typical tensile stress-crack opening response that will be used to explain how the above criteria can be fulfilled.

Figure 2-1 (a) Typical relation between fibre bridging stress and crack opening (Li, 2019) and (b) an example of the sample used for the single crack tension test.

The strength-based criterion described in Equation 2-1 stipulates that the cracking strength would not exceed the bridging capacity of fibres:

\[ \sigma_{fc}, \sigma_c < \sigma_0 \]  \hspace{1cm} (2-1)

where \( \sigma_{fc} \) is the stress required to initiate the first crack, \( \sigma_c \) is the stress required to form another crack (multiple cracks are formed already), and \( \sigma_0 \) is the maximum fibre bridging stress.

The cracking strength of EGCs is normally influenced by the internal flaw size and \( K_m \) and would be dependent on the fibre bridging properties if the internal flaw is bridged by the fibre (Li, 2019). Herein, a higher \( K_m \) would result in larger cracking strength, which could increase the size of active flaw (Li, 2019). The active flaw means the flaw that can induce the new crack when the tensile stress is lower than the fibre bridging capacity (Xu et al., 2022). Once the crack is formed, it will propagate along the weak zone, e.g., the interface between aggregate and cement paste (Li and Wang,
Further, additional cracks will be initiated from the smaller size flaws as the tensile load increases. It should be noted that the localisation of fracture would happen if the tensile load required to generate a new crack from a flaw is higher than the bridging capacity of fibres at any of the formed multiple cracks (Li, 2019).

The multiple cracking behaviour is strongly associated with fibre bridging (Zhang et al., 2020b). The distinct difference between ordinary FRC and ECCs in terms of the uniaxial tensile behaviour lies in the different crack propagation modes (see Figure 1-1). The crack propagation of normal FRC follows the Griffith crack propagation mode, where the crack opening increases indefinitely with crack length while the ambient load must be reduced to ensure equilibrium, leading to strain-softening behaviour (Li, 2019). By contrast, the flat crack propagation mode is normally observed in ECCs or EGCs, where the ambient load and the crack opening are maintained as constant as the indefinite extension of the crack length (Li, 2019, Yang and Li, 2007). To achieve such crack propagation mode, the following energy-based criterion must be fulfilled, i.e., the maximum complementary energy ($J'_b$) for fibre bridging must be greater than the energy consumed by fracturing the matrix ($J_{tip}$):

\[
\begin{align*}
J'_b &\geq J_{tip} = \sigma_{ss} \delta_{ss} - \int_0^{\delta_{ss}} \sigma(\delta) \, d\delta = \frac{K_m^2}{E_m} \\
&= \sigma_0 \delta_0 - \int_0^{\delta_0} \sigma(\delta) \, d\delta = J'_b
\end{align*}
\]

where $\delta_0$ and $\delta_{ss}$ are the crack openings corresponding to the maximum fibre bridging stress ($\sigma_0$) and steady-state bridging stress ($\sigma_{ss}$), respectively, and $E_m$ is the matrix elastic modulus.

To verify the criteria above, a series of experiments need to be performed to attain the fibre bridging stress-crack opening response (Figure 2-1a), $E_m$ and $K_m$. By conducting the uniaxial tensile test on the dog-bone shaped specimen with a notch around its middle part (Figure 2-1b), the relation between fibre bridging stress and crack opening can be determined experimentally (Pereira et al., 2012). This relation can be computed theoretically by considering the two-way pull-out, matrix microspalling and Cook-Gordon effects, where the detailed computation procedure has been well summarised in Ref. (Yang et al., 2008). A set of micromechanical parameters including fibre, matrix and fibre-matrix interface properties are required as inputs for the above theoretical analysis, most of which can be measured experimentally (Yang et al., 2008).
2.3.2 Fibre-matrix interaction

Based on Section 2.3, the tensile behaviour of EGCs could be tailored by altering the properties of microstructural components (matrix, fibre and fibre-matrix interface). For instance, adjusting the fibre properties such as strength, elastic modulus and aspect ratio can vary $\sigma_0$ and $J'_b$ (Zhang et al., 2020b). The influences of various parameters on the properties of matrix and fibre-matrix interface which are closely associated with the tensile behaviour of EGCs have been increasingly studied, as presented below.

2.3.2.1 Properties of matrix

As discussed previously, $K_m$ is an important parameter for EGCs and should be limited, which can be measured through a three-point bending test (Li, 2019). Figure 2-2 shows some scatters of $K_m$ and $J_{tip}$ collected from the existing studies on EGCs. In general, $J_{tip}$ of most matrices rises with the increasing $K_m$. The measured $K_m$ was in the range of 0.07-0.60 MPa·m$^{1/2}$, while the corresponding $J_{tip}$ ranged from 0.57 Jm$^{-2}$ to 65.80 Jm$^{-2}$. Most EGC matrices had smaller $K_m$ values compared to the most commonly used M45 ECC (about 0.60 MPa·m$^{1/2}$ (Wang and Li, 2007)), but higher $J_{tip}$ values (around 15 Jm$^{-2}$ (Wang and Li, 2007)).

Regarding the effect of precursor, the presence of SS, zeolite or gypsum free slag (GFS) can significantly reduce $K_m$ of the matrix without the above materials (16-68%) (Zhao et al., 2021b, Kan et al., 2020c, Nematollahi et al., 2017e). Nevertheless, the results from Ref. (Zhao et al., 2021b) contradicted Equation (2-2), where $J_{tip}$ of the matrix made from SS went up with the reducing $K_m$. Irrespective of sand addition, replacing GGBS with 50% FA led to an increased $K_m$ (Alrefaei and Dai, 2018), which was inconsistent with the effect of FA in ECC mixes (Wang and Li, 2007). The lower reactivity of FA compared to GGBS could weaken $K_m$. Using 10% RM to replace GGBS and SF and rising the dosage of IFA (0-40%) increased $K_m$, while the presence of RM reduced $J_{tip}$ under both ambient temperature and heat curing regimes (Kan and Wang, 2022, Kan et al., 2020b). Differently, increasing the content of IFA from 0% to 10% resulted in a 29% rise in $J_{tip}$, while the further addition of IFA to 40% did not have a prominent influence.
Figure 2-2 Scatters of $K_m$ and $J_{tip}$ of EGCs (data adapted from Refs. (Kan and Wang, 2022, Li et al., 2021a, Nguyễn et al., 2021, Kan et al., 2021, Zhao et al., 2021b, Kan et al., 2020b, Kan et al., 2020c, Kan et al., 2020a, Zhang et al., 2020c, Nematollahi et al., 2017e, Nematollahi et al., 2017d, Nematollahi et al., 2017b, Nematollahi et al., 2016, Nematollahi et al., 2014)).

$K_m$ can be also affected by the type, dosage and properties of alkaline activator. By comparing four different activator types, the mixture activated by a combination of NaOH and Na$_2$SiO$_3$ had the highest $K_m$ (0.436 MPa·m$^{1/2}$) and $J_{tip}$ (22.4 Jm$^{-2}$), while both were the lowest when Ca(OH)$_2$ was used as the activator (0.086 MPa·m$^{1/2}$ and 4.1 Jm$^{-2}$) (Nematollahi et al., 2014), which is consistent with the findings reported in Ref. (Nematollahi et al., 2017b). Increasing W/s from 0.20 to 0.23 can effectively lower $K_m$ and $J_{tip}$ of EGCs (Nematollahi et al., 2017b, Nematollahi et al., 2016). As indicated in Ref. (Zhang et al., 2020c), both $K_m$ and $J_{tip}$ went up first when the silicate modulus of the activator changed from 0.8 to 1.0 and after which, they dropped, while adjusting the silicate modulus from 1.0-1.2 may lead to a different amount of reaction products along with disparate nature and thus different values of $K_m$. Due to the higher compressive strength, the mixture with more sodium metasilicate pentahydrate powder exhibited a higher $K_m$ and $J_{tip}$ (Nguyễn et al., 2021).

Independent of binder and sand types, the addition of sand considerably increased $K_m$ and $J_{tip}$ due to the increased energy consumption to propagate the crack (Nematollahi et al., 2016, Alrefaei and Dai, 2018, Li et al., 2001, Pan et al., 2011). Both parameters were strongly sensitive to the sand size (Nematollahi et al., 2016).
For instance, \(K_m\) and \(J_{tip}\) of mixtures containing coarse sand (1180 \(\mu\)m) were 6-18% and 23-30% lower than those of mixtures made of fine sand (212 \(\mu\)m) when a constant W/s was adopted. This was because the crack propagation path in the mixture containing coarse sand was less tortuous than that in the mix incorporating fine sand, consuming less energy (Nematollahi et al., 2016). There were no obvious changes in \(K_m\) and \(J_{tip}\) with curing age (Kan et al., 2020a, Kan et al., 2021). Applying elevated temperature to cure the sample can reduce both \(K_m\) and \(J_{tip}\) as the microstructure of the matrix after ambient temperature curing was denser (Kan and Wang, 2022, Nematollahi et al., 2017a).

In summary, \(K_m\) of EGCs is highly related to its microstructure especially the amount and nature of reaction products. To attain superior tensile behaviour of EGCs, \(K_m\) should be strictly controlled.

### 2.3.2.2 Properties of fibre-matrix interface

As aforementioned, the bridging fibres play an essential role after the crack initiation. As the crack propagates with the increasing crack opening, the bridging fibres de-bond and stretch across the crack interface until the complete pull-out or rupture (Li, 2019). This pull-out behaviour is associated with the fibre-matrix interface properties that can be measured by conducting a single fibre pull-out test (see Figure 2-3a). A typical test curve in a single fibre pull-out test is illustrated in Figure 2-3b, which can be mainly classified into two stages: (1) de-bonding and (2) slippage/sliding (Redon et al., 2001). To pull out a fibre (e.g., PVA), certain stress is first needed to overcome the chemical bond \(G_d\) to de-bond it, followed by slippage/sliding depending on the frictional bond \(\tau_0\) and slip-hardening coefficient \(\beta\). These three parameters can be evaluated as follows (Redon et al., 2001):

\[
\begin{align*}
G_d &= \frac{2(F_{pa} - F_{pb})^2}{\pi^2 E_f d_f^3} \\ 
\tau_0 &= \frac{F_{pb}}{\pi d_f L_e} \\ 
\beta &= \frac{d_f}{L_e} \left( \frac{1}{\pi \tau_0 d_f} \left( \frac{\Delta F_p}{\Delta S'} \right) \right)_{S' \to 0} + 1
\end{align*}
\]

where \(F_{pa}\) is the maximum force when debonding length equals the embedment length of fibre, \(F_{pb}\) is the force at the start of fibre sliding, \(E_f\) and \(d_f\) are the elastic modulus and diameter of fibre, \(L_e\) is the embedment length, and \(S'\) is the sliding displacement.
Figure 2-3 (a) An example of a single fibre pull-out test setup, and (b) typical curves from single fibre pull-out tests (Zhang et al., 2020c, Redon et al., 2001).

Table 2-2 summarises the results of $G_d$, $\tau_0$ and $\beta$ obtained from the existing studies on EGCs, considering the effects of supplementary materials (zeolite, IFA, GFS), activator (type, content, silicate modulus), W/s, fibre (type, aspect ratio), and curing condition. Regardless of fibre type, the measured $G_d$, $\tau_0$ and $\beta$ of EGCs were in ranges of 0.46-6.10 Jm$^{-2}$, 0.55-6.53 MPa and -0.06-0.5, respectively. Compared to M45 ECC with PVA fibres (Wang and Li, 2007), most EGC mixtures exhibited smaller $G_d$, $\tau_0$ and $\beta$.

Table 2-2 Summary of single fibre pull-out test results from existing studies.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Binder</th>
<th>Fibre</th>
<th>Variable</th>
<th>$G_d$ (Jm$^{-2}$)</th>
<th>$\tau_0$ (MPa)</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choi et al. (2015)</td>
<td>GGBS (paste)</td>
<td>PVA</td>
<td>W/s (0.40, 0.45)</td>
<td>0.71, 1.13</td>
<td>1.14, 1.27</td>
<td>0.012</td>
</tr>
<tr>
<td>Nematollahi et al. (2017a)</td>
<td>FA (paste)</td>
<td>PVA</td>
<td>-</td>
<td>1.31</td>
<td>1.3</td>
<td>0.499</td>
</tr>
<tr>
<td>Nematollahi et al. (2017b)</td>
<td>FA (paste)</td>
<td>PVA</td>
<td>Activator type, W/s (0.20, 0.23)</td>
<td>0.59, 1.31, 3.41</td>
<td>0.87, 1.30, 1.73</td>
<td>0.03, 0.46, 0.50</td>
</tr>
<tr>
<td>Nematollahi et al. (2017d)</td>
<td>FA+GGBS (paste)</td>
<td>PVA</td>
<td>Fibre type, curing condition</td>
<td>1.03 (PVA)</td>
<td>1.32, 1.36, 2.14</td>
<td>0.014, 0.019, 0.041</td>
</tr>
<tr>
<td>Nematollahi et al. (2017c)</td>
<td>FA+GGBS or GFS (paste)</td>
<td>PVA</td>
<td>Binder type, curing condition</td>
<td>0.46-1.03</td>
<td>1.14-2.14</td>
<td>0.021-0.049</td>
</tr>
<tr>
<td>Ohno and Li (2018)</td>
<td>FA (mortar)</td>
<td>PVA</td>
<td>-</td>
<td>6.1</td>
<td>0.7</td>
<td>0.33</td>
</tr>
<tr>
<td>Zhang et al. (2020c)</td>
<td>FA+GGBS (paste)</td>
<td>PVA</td>
<td>Silicate modulus (0.8-1.5)</td>
<td>1.57-3.20</td>
<td>1.81-4.01</td>
<td>0.25-0.39</td>
</tr>
<tr>
<td>Kan et al. (2020c)</td>
<td>FA+Zeolite (mortar)</td>
<td>PVA</td>
<td>Zeolite content (0%, 6%)</td>
<td>1.16, 1.91</td>
<td>1.63, 6.53</td>
<td>-</td>
</tr>
<tr>
<td>Kan et al. (2020b)</td>
<td>GGBS+SF+IFA (mortar)</td>
<td>PE</td>
<td>IFA content (0%, 10%, 40%)</td>
<td>-</td>
<td>0.73, 0.95, 1.10</td>
<td>0.003, 0.004, 0.006</td>
</tr>
<tr>
<td>Choi et al. (2020)</td>
<td>GGBS (paste)</td>
<td>PE</td>
<td>-</td>
<td>-</td>
<td>1.49</td>
<td>-0.06</td>
</tr>
<tr>
<td>Choi et al. (2021)</td>
<td>GGBS (paste)</td>
<td>PE</td>
<td>Aspect ratio of fibre (375, 750, 1500)</td>
<td>-</td>
<td>0.818, 1.437</td>
<td>-0.0017, -0.0474</td>
</tr>
<tr>
<td>Nguyễn et al. (2021)</td>
<td>FA (paste)</td>
<td>PE</td>
<td>Activator content</td>
<td>-</td>
<td>0.55, 0.63</td>
<td>-0.0008, -0.0127</td>
</tr>
</tbody>
</table>
Unlike the influence on $K_m$, the inclusion of zeolite increased both $G_d$ and $\tau_0$ of the EGC with no zeolite by 65% and 301% due to the facilitated reaction process caused by the zeolite (Kan et al., 2020c). The effects of GFS and IFA on the interface properties especially $\tau_0$ and $\beta$ followed the trend of $K_m$ (Kan et al., 2020b, Nematollahi et al., 2017e), which can be attributed to the increased fracture surface toughness as a positive correlation was found between it and fracture toughness (Lange et al., 1993). Hence, the contact areas between fibres and the matrix are increased, leading to a larger $\tau_0$. Besides, a jamming effect can occur more easily because of the increased contact area and thereby a larger $\beta$. $G_d$ is closely related to the type and composition of the reaction products attached to the surface of the fibre (Wang and Li, 2007, Zhang et al., 2020c).

Increasing W/s from 0.40 to 0.45 in the GGBS-based EGC reduced $G_d$ and $\tau_0$ but did not change $\beta$ (Choi et al., 2015), which agrees well with the finding for the FA-based EGC when oil-coated PVA fibres were used (Nematollahi et al., 2017b). Decreasing W/s would lead to fewer reaction products adhered to the fibre’s surface and thereby lower $G_d$. By contrast, the oil-coating can weaken the jamming effect during the slippage and thus, $\beta$ was insignificantly affected by adjusting W/s. However, $\tau_0$ of the FA-based EGC was found to rise by 33% when W/s was increased to 0.23, which is opposed to the observation in ECCs that $\tau_0$ dropped with the increasing water content (Nematollahi et al., 2017b). The mixture activated by KOH and $K_2SiO_3$ exhibited a higher $G_d$ but lower $\tau_0$ and $\beta$ compared to that using NaOH and Na$_2$SiO$_3$, where the higher $G_d$ in the EGC with K-based activator can be attributed to the loss of oil-coating agent on the PVA fibre’s surface as a result of the higher alkalinity of KOH solution (Nematollahi et al., 2017b). The changes in $G_d$ and $\beta$ with the silicate modulus of the activator (0.8-1.5) followed the trend of $K_m$, while the tendency of $\tau_0$ was different, which can be ascribed to the synergistic effect of fracture surface toughness and shrinkage-induced normal stress. Both $\tau_0$ and $\beta$ went up with the increasing dosage of sodium metasilicate pentahydrate powder, consistent with the trend of $K_m$ (Nguyễn et al., 2021).

By comparing PE fibre and PVA fibre, no chemical bond was observed for the EGC with PE fibres and further, its $\tau_0$ and $\beta$ were 36% and 54% lower in comparison with the PVA fibre reinforced EGC (Nematollahi et al., 2017d). These reduced interface properties caused by PE fibre can be attributed to its hydrophobic feature.
Similarly, as seen in Table 2-2, all PE fibre reinforced EGC mixes did not have a $G_d$ along with a slip-softening behaviour ($\beta$ is less than 0). According to Ref. (Choi et al., 2016), $\tau_0$ of the EGC was reduced from 1.44 MPa to 0.82 MPa when the aspect ratio of the used PE fibre declined from 1500 to 750 but remained constant when the aspect ratio further dropped to 375. Due to the denser microstructure, most ambient-cured EGCs presented better interface properties than heat-cured EGCs (Nematollahi et al., 2017e).

Regardless of reinforcing fibre type, the interface properties are associated with $K_m$, composition and amount of the reaction products on the fibre’s surface, and shrinkage-induced normal stress, which should be adequate to promote complete fibre pull-out while avoiding fibre rupture.

2.3.3 Strain-hardening indices

Both strength-based ($PSH_{strength}$) and energy-based ($PSH_{energy}$) indices can be used to quantify the possibility of achieving strain-hardening and multiple cracking behaviour for EGCs. To attain a robust strain-hardening and saturated multiple cracking for ECCs, $PSH_{strength}$ and $PSH_{energy}$ should be higher than 1.2 and 2.7, respectively (Kanda and Li, 2006, Kanda and Li, 1998). These values were also used here as the requirements for defining the robust tensile behaviour of EGCs. Most studies employed single crack tension tests (Figure 2-1b) to estimate these index values (Zhao et al., 2021b, Kan et al., 2020b, Kan and Wang, 2022, Kan et al., 2021), while a few studies derived them from the theoretical relation between fibre bridging stress and crack opening (Zhang et al., 2020c, Nematollahi et al., 2017d, Nematollahi et al., 2017e). Herein, only the studies that have determined both indices were discussed. Most mixtures can achieve a robust strain-hardening behaviour under uniaxial tension considering both indices, which were confirmed by the corresponding tensile stress-strain curves and cracking patterns.

With the increase of IFA content from 0% to 10% and 40% in the GGBS-SF based EGC, $PSH_{strength}$ was consistently increased, while $PSH_{energy}$ went up first and then dropped (Kan et al., 2020b). The better $PSH_{energy}$ can be ascribed to the higher $\sigma_0$ as a result of stronger $\tau_0$. For all mixtures, both $PSH_{strength}$ (1.30-2.93) and $PSH_{energy}$ (30.36-38.91) fulfilled the requirements of robust strain-hardening behaviour mentioned above for ECCs. Moreover, the trend of tensile strength followed the tendency of $PSH_{energy}$, while the trend of tensile strain capacity was consistent with
that of $PSH_{strength}$. Under ambient temperature curing, no notable effects in $PSH_{strength}$ and $PSH_{energy}$ were observed when 10% RM was adopted to replace GGBS and SF, while the mixtures containing RM had larger $PSH_{strength}$ and $PSH_{energy}$ values (1.74 and 19.54) than those of the EGC without RM (1.63 and 16.28) under heat curing (Kan and Wang, 2022). These results were in good agreement with that for tensile properties. As mentioned in Section 2.3.2, the inclusion of SS led to increased $J_{tip}$ and the calculated $PSH_{energy}$ value was the lowest (6.58) at the highest SS substitution level (Zhao et al., 2021b). Besides, the tensile properties were more sensitive to $PSH_{energy}$, instead of $PSH_{strength}$. Regardless of curing regime, EGCs with FA and GFS exhibited lower $PSH_{strength}$ and $PSH_{energy}$ values (1.10-1.11 and 1.73-2.07) than the mixes with FA and GGBS (1.42-1.44 and 2.09-2.38), indicating that the interface properties especially $\tau_0$ and $\beta$ played a more dominant role than $K_m$ (Nematollahi et al., 2017e). All studied mixes still presented conspicuous strain-hardening behaviour along with tensile strain capacity of 2.6-4.2% and reasonable variability although most of their indices were lower than those for ECCs to achieve robust strain-hardening behaviour. The tensile properties of all mixtures were positively correlated with these indices. As seen in Figure 2-4a, the use of activator with silicate modulus of 1.2 to fabricate the EGC can lead to the highest $PSH_{strength}$ (2.63) compared to others with different silicate moduli, which can be attributed to the lower $K_m$ and $\beta$ as well as higher $\tau_0$ (Zhang et al., 2020c). However, both indices did not have a clear correlation with tensile properties.

![Figure 2-4](image)

Figure 2-4 Effects of (a) activator modulus (Zhang et al., 2020c) and (b) curing age (Kan et al., 2021) on strain-hardening indices of EGCs.
Because of lower $\tau_0$ and $\beta$, the PE fibre reinforced EGC exhibited higher index values than the PVA fibre reinforced EGC under ambient temperature curing, consistent with the tensile strain capacity (Nematollahi et al., 2017d), due to the better fibre bridging behaviour as fewer fibres would undergo breaking or rupturing.

Regarding the influence of curing regime, it was revealed that heat-cured mixtures had higher strain-hardening indices than ambient-cured EGCs (Nematollahi et al., 2017d, Kan and Wang, 2022), which can be mainly attributed to the smaller $K_m$ and $J_{tip}$. It should be noted that only the tensile strain capacity of these mixtures had a positive relation with the indices, while their tensile strengths exhibited opposite trends. A different conclusion was made in terms of the effect of curing condition, where ambient-cured EGCs had higher strain-hardening indices than those with heat curing (Nematollahi et al., 2017e), as the strain-hardening indices can be affected more significantly by $\tau_0$ and $\beta$ as compared to $K_m$. Both tensile strength and strain capacity showed a good correlation with $PSH_{strength}$ and $PSH_{energy}$. As presented in Figure 2-4b, there was no clear trend in $PSH_{strength}$ of the FA-GGBS based EGC when the curing period changed, while $PSH_{energy}$ was consistently increased until 56 d (Kan et al., 2021). The tensile properties were more sensitive to $PSH_{energy}$, where the EGC mixture achieved the highest tensile strength and strain capacity at 56 d.

In summary, the strain-hardening indices of most EGCs had a positive relationship with their tensile properties. $\tau_0$ and $\beta$ can affect the strain-hardening indices more significantly as opposed to $K_m$ and $G_d$. The index values for EGCs to achieve a robust strain-hardening and saturated multiple cracking may be lower than those for ECCs, which need to be confirmed with more data.

2.4 Engineering properties of EGCs

2.4.1 Workability

Workability is an important property for EGCs, which was generally assessed using the flow table test. Most available studies have focused on the effect of fibre in terms of type, content and aspect ratio on the workability of EGCs, the results of which are shown in Figure 2-5. Regardless of fibre type, a consistent trend can be found that increasing the fibre content can considerably decrease the slump flow of EGCs, due to the reduced packing density and increased friction between fibres and between fibres and the matrix (Ranjabar and Zhang, 2020, Khayat et al., 2019). A critical value exists for the fibre dosage and exceeding it can lead to a substantial reduction in workability.
and an increased possibility of fibre-ballling or fibre-clumping, which is associated with the fibre aspect ratio (Ranjbar and Zhang, 2020). The slump flow of EGC mixtures with PVA fibres with an aspect ratio of 200-300 was about 15% lower than that with a fibre aspect ratio of 90-120 since the higher aspect ratio of fibre may lead to more absorption of water or solution (larger fibre surface area) and increasing interaction with other solid particles and thereby impairing the flowability (Farooq et al., 2019, Farooq et al., 2022, Zahid et al., 2020). Under the same Agg/b and molarity of NaOH solution, the EGC with steel fibres presented higher flowability than that with PVA fibres (Farooq et al., 2019), which can be ascribed to the strong hydrophilic feature of PVA fibres and smaller aspect ratio of steel fibres. Regarding the effect of fibre type, rigid fibres (e.g., steel) tend to raise the yield stress while flexible fibres (e.g., PVA, PP) typically increase the viscosity as they can be entangled as an S-shape structure to block the movement of particles (Khayat et al., 2019, Yamanoi and Maia, 2010). Apart from mono-fibre reinforced EGCs, some studies have investigated the influence of fibre hybridisation on the workability of EGCs (Alrefaei and Dai, 2018). Utilising RTS fibres to substitute PVA fibres led to a 9-16% drop in slump flow as compared with the mono-PVA fibre reinforced EGC (Wang et al., 2020). This is because RTS fibres are less uniform in geometry and dimension than industrial steel fibres.

Figure 2-5 Effects of fibre type and dosage on slump flow of EGCs (data adapted fromRefs. (Farooq et al., 2019, Wang et al., 2020, Humur and Çevik, 2022a)).

Note: 8 M and 12 M represent the molarity of sodium hydroxide solution.
Except for the fibre effect on the workability of EGCs, a few studies explored the influence of parameters related to the matrix on the workability of EGCs. Owing to the spherical shape and low reactivity of FA, the slump flow of FA-GGBS based EGCs was higher than that prepared by GGBS only (Alrefaei and Dai, 2018, Farooq et al., 2022, Humur and Çevik, 2022b). Increasing the molarity of NaOH solution from 8 M to 12 M caused an 8-28% reduction in slump flow of EGCs (Farooq et al., 2019), which can be attributed to the accelerated dissolution and polycondensation kinetics (Lu et al., 2021). However, an opposite trend was reported in Ref. (Salami et al., 2017), which can be explained by the different nature of the precursor (FA against POFA). Similar to the effect of water-to-binder ratio (W/b) in cement-based materials, raising W/s from 0.40 to 0.45 improved the workability of the EGC in terms of slump flow and V-funnel flow time (Choi et al., 2015). Increasing Agg/b consistently decreased the workability of EGCs due to the increased inter-particle friction and specific surface area (Wang et al., 2021b, Kumar et al., 2022). The increased specific surface area would require more paste to cover the aggregates. On the other hand, the particle packing can be enhanced with the increase of aggregate content and less paste would be required to fill the voids (Kondepudi et al., 2022). These two effects would compete simultaneously and the presence of a proper aggregate content would lead to better particle packing as well as acceptable workability for the EGC. In addition, using 20% copper slag to replace silica sand was beneficial to the workability of the EGC (Yaswanth et al., 2022b).

2.4.2 Setting time

Setting time is not a focus among the existing studies on EGCs although it is crucial for engineering applications (Zhong and Zhang, 2022). It was reported that the initial setting time and final setting time of the GGBS-based EGC were only 25 min and 30 min, respectively, which were much lower compared with those of the FA-based EGC (270 min and 300 min) (Farooq et al., 2022). Using blended FA and GGBS as the precursor can achieve an acceptable initial and final setting time for the EGC (65-80 min and 90-110 min). By altering Agg/b of the EGC (0-0.4), both initial and final setting time declined due to the decreased activator content (Wang et al., 2021b). Increasing the PVA fibre length from 8 mm to 13 mm did not significantly change the setting time of the EGC (Farooq et al., 2022), while raising either PVA or RTS fibre content shortened the setting time of the EGC (Wang et al., 2020). It should be noted that for conventional and some specific applications, the control of setting time is
rather essential as it can affect the placing process as well as hardened properties (Ranjbar et al., 2020).

2.4.3 Drying shrinkage

As mentioned earlier, coarse aggregates are normally eliminated from the mix designs of both ECCs and EGCs, which could lead to a high drying shrinkage during the hardening process (Zhang et al., 2009a). Further, several mix designs of EGCs in Table 2-1 even did not include aggregates (i.e., pastes), making them more susceptible to shrinkage-induced cracking. Owing to the excellent shape stability of aggregates, the drying shrinkage resistance of the EGC tends to be higher when the incorporated aggregate content is larger (Wang et al., 2021b). The effects of PVA and RTS fibre content on the drying shrinkage of EGCs were reported in Ref. (Wang et al., 2020) (Figure 2-6). It was found that the drying shrinkage resistance of the EGC was not enhanced when the PVA fibre dosage increased from 1.5% to 2.0% while using RTS fibres to partially replace PVA fibres can improve the drying shrinkage resistance of the mixture. For instance, replacing PVA fibre with 0.5% RTS fibre in the EGC led to a 73% drop in drying shrinkage at 28 d (1548 με) as compared with the mix with 2.0% PVA, which was comparable to a traditional ECC. In addition to the intrinsic properties of these recycled fibres, the improved shrinkage resistance can be associated with the reduced porosity and synergistic effect of hybrid fibres in controlling the cracks.

Figure 2-6 Drying shrinkage of EGCs with different fibre type and content (Wang et al., 2020).
2.4.4 Compressive behaviour

To date, there was about 36% of the mixes exhibiting a compressive strength between 10 MPa and 40 MPa. Although some of them have superior tensile behaviour, they can only be used for some non-structural applications due to their low compressive strengths (Li, 2019). Around 37% of them exhibited a compressive strength of 40-70 MPa, which is adequate for the requirements of most structural applications. Figure 2-7 shows the effect of curing age on the compressive strength of EGCs, indicating that regardless of binder and reinforcing fibre types, the compressive strength of EGCs developed rapidly up to 28 d, after which the compressive strength was either increased slightly or even decreased (Choi et al., 2019a, Kan et al., 2020a, Kan et al., 2021). The reduced compressive strength can be associated with the cracking induced by shrinkage. The highest compressive reached in the EGC was 222 MPa but its tensile strain capacity was less than 0.4% (Lao et al., 2022). As a promising EGC type, the highest compressive strength obtained in the FA-GGBS based EGC was about 100 MPa at 28 d along with a tensile strength of 5.77 MPa and a tensile strain capacity of 5.81% (Kan et al., 2021). Only about 26% of the EGC mixes had higher compressive strength than M45 ECC (about 68 MPa) (Wang and Li, 2007).

![Figure 2-7 Effect of curing age on compressive strength of EGCs](data adaptéed from Refs. (Choi et al., 2019a, Kan et al., 2020a, Kan et al., 2021)).

The inclusion of some polymeric fibres such as PP and PVA fibres weakened the compressive strength of EGCs although they resulted in substantial improvement in tensile strength (Farooq et al., 2019, Wang et al., 2020). Unlike steel fibres, the relatively lower stiffness of these polymeric fibres may entrap more air voids during
the manufacturing process, resulting in higher local fractures near the fibres and thus diminishing the compressive strength (Ranjbar and Zhang, 2020). Several studies on cementitious composites indicated that the presence of PVA fibres can result in higher porosity for the resultant composites (Long et al., 2021, Liu et al., 2021). Although the compressive strength of EGCs was reduced after adding these fibres, the compressive ductility was enhanced along with higher integrity (Kan et al., 2020a, Wang et al., 2020).

Besides compressive strength, elastic modulus is another important property for structural design. Figure 2-8 shows the elastic modulus against compressive strength along with some existing equations for predicting the elastic modulus of Portland cement concrete (ACI 318, 2008, CEB-FIP model code 1990: Design code, 1990) and geopolymer concrete (Lee and Lee, 2013). The elastic modulus of Portland cement concrete can be predicted according to the ACI 318 model (Equation (2-4)) and CEB-FIP model (Equation (2-5)) as follows:

\[
E_s = 0.043 \times \rho_s \times \sqrt{f_c} \quad (2-4)
\]
\[
E_s = 18275 \times \frac{f_c^{1/3}}{10} \quad (2-5)
\]

where \(E_s\) is the elastic modulus, \(\rho_s\) is the density, and \(f_c\) is the quasi-static compressive strength.

Additionally, Lee and Lee (2013) proposed an equation to predict the elastic modulus of FA-GGBS based concrete:

\[
E_s = 5300f_c^{1/3} \quad (2-6)
\]

Similar to these equations, the elastic modulus of most EGC mixtures is positively correlated with the compressive strength, while some conflicting results were reported that increasing Agg/b reduced the compressive strength of the EGC but improved its elastic modulus (Kumar et al., 2022), implying that the elastic modulus can be affected by aggregate more noticeably compared to compressive strength. The elastic modulus of EGCs is also related to the properties of the interfacial transition zone (ITZ) in EGCs. It was found that an enhanced ITZ led to an improvement in elastic modulus of geopolymer concrete (Tang and Li, 2022, Fonseca et al., 2011). Due to the absence of coarse aggregates, the elastic modulus of EGCs ranging from 0.8 GPa to 31.2 GPa was generally lower than that of normal and geopolymer concrete.
2.4.5 Uniaxial tensile behaviour

Since uniaxial tensile behaviour is the most key property of EGCs, many studies explored the effects of different factors on it in terms of stress-strain response, tensile strength and strain capacity, tensile strain energy, and fracture processes, which are comprehensively reviewed in this section.

2.4.5.1 Tensile stress-strain response

Similar to ECCs, the tensile stress-strain responses of EGCs can be divided into three main regions: a linear elastic region, a strain-hardening region, and a strain-softening region. Some typical examples considering different factors are depicted in Figure 2-9. The stress at the transition point between the linear elastic region and the strain-hardening region is called first cracking strength (Alrefaei and Dai, 2018), while the highest point of stress is regarded as tensile strength and the corresponding strain is tensile strain capacity. Besides, the tensile strain energy known as strain energy density per unit volume can be used to reflect the strain-hardening degree of EGCs, which can be determined by integrating the region of the tensile stress-strain curve prior to the strain-softening region (Wille et al., 2014). As indicated, most EGC mixtures from the existing studies can exhibit clear strain-hardening behaviour, while only a few of them presented pure strain-softening behaviour (e.g., those reinforced with low-strength fibres (Farooq et al., 2019)).
Figure 2-9 Effects of (a) precursor (Ling et al., 2019), (b) activator (Nguyễn et al., 2019b), and (c) aggregate (Lương et al., 2021) on tensile stress-strain response of EGCs.

2.4.5.2 Tensile strength and tensile strain capacity

The available data on the first cracking strength is summarised in Figure 2-10a, indicating that the first cracking strength generally rises with the increase of tensile strength. As mentioned previously, the first cracking strength of EGCs is related to $K_m$ and most studies affirmed it, where the first cracking strength of EGCs tended to be larger at a higher $K_m$ (Nematollahi et al., 2016, Nematollahi et al., 2017b, Nematollahi et al., 2017d, Nematollahi et al., 2017e, Alrefaei and Dai, 2018, Zhang et al., 2020c, Kan et al., 2020a, Nguyễn et al., 2021, Kan and Wang, 2022). Nevertheless, some inconsistent results were also reported (Kan et al., 2020b, Kan et al., 2020c, Kan et al., 2021), since the inclusion of fibres can alter the internal pore structure of EGCs and the first cracking strength is also influenced by the pore size. In addition, the fibre bridging behaviour can influence the first cracking strength as some pores or flaws can
be bridged by the fibres before tensile loading. This was confirmed by some studies that the mixtures containing fibres with different types or contents exhibited discrepant first cracking strengths when they shared the same matrix (Alrefaei and Dai, 2018, Ohno and Li, 2018).

The relationships between tensile strength and compressive strength as well as tensile strain capacity for EGCs are shown in Figures 2-10b and c, respectively, revealing that the tensile strength of most EGCs rises with the increase of either compressive strength or tensile strain capacity (when the strain capacity is greater than 2%). In comparison with M45 ECC (Wang and Li, 2007), about 29% of EGC mixtures exhibited a higher tensile strength (> 4.86 MPa), while approximately 66% of mixes had a higher tensile strain capacity (> 2.49%). As mentioned earlier, the tensile properties of EGCs were strongly associated with the strain-hardening indices. To avoid replication, the studies discussed in Section 2.3.3 were not analysed here.
Figure 2-10 Relations between tensile strength and (a) first cracking strength, (b) compressive strength and (c) tensile strain capacity for EGCs (data adapted from Refs. (Lee et al., 2012, Nematollahi et al., 2015, Choi et al., 2015, Nematollahi et al., 2016, Lee et al., 2017, Nematollahi et al., 2017b, Nematollahi et al., 2017c, Nematollahi et al., 2017d, Nematollahi et al., 2017e, Nguyen et al., 2018, Alrefaei and Dai, 2018, Ohno and Li, 2018, Choi et al., 2019b, Choi et al., 2019a, Farooq et al., 2019, Ling et al., 2019, Zhang et al., 2020c, Zahid et al., 2020, Kan et al., 2020a, Kan et al., 2020c, Kan et al., 2020b, Li et al., 2021a, Zhao et al., 2021b, Choi et al., 2021, Kan et al., 2021, Nguyễn et al., 2021, Kan and Wang, 2022, Cai et al., 2022, Kumar et al., 2022, Yaswanth et al., 2022a, Ohno and Li, 2014, Al-Majidi et al., 2017, Luong et al., 2021, Farooq et al., 2022, Yoo et al., 2022)).
It was found that using 10-30% GGBS to partially replace FA improved the tensile strength of FA-based EGCs by 9-45%, while the corresponding tensile strain capacity was 48-76% lower (Ling et al., 2019), which can be also reflected in Figure 2-9a. The enhanced strength caused by the addition of GGBS was due to the increased amount of C-A-S-H and C-S-H gels, while the reduced strain capacity can be attributed to the lower stress index (i.e., ratio of tensile strength and first cracking strength). However, different results were found in another study that replacing 50% GGBS with FA impaired both tensile strength and strain capacity of the EGC due to the smaller strain-hardening indices (Alrefaei and Dai, 2018). The addition of 3% and 6% zeolite can increase the tensile strength and strain capacity of FA-based EGCs, whereas excessive addition of zeolite (9%) impaired them (Kan et al., 2020c), due to the combined effect of increased $\tau_0$ and reduced $K_m$ after the presence of zeolite (see Section 2.3.2). With SF, the tensile strength and strain capacity of the GGBS-based EGC were enhanced by 26% and 13%, respectively, owing to the increased packing density and densified microstructure (Choi et al., 2019b).

Irrespective of the used matrix component, increasing W/s of EGCs led to a reduced tensile strength and strain capacity, mainly due to the drop in fibre bridging capacity as a result of weaker interface properties (Choi et al., 2015, Lee et al., 2012, Choi et al., 2019b, Nematollahi et al., 2016, Nematollahi et al., 2017b). The reduced fibre bridging capacity can be evidenced by the values of $PSH_{energy}$. Although rising W/s from 0.20 to 0.23 resulted in an improved $\tau_0$ for the EGC, its $G_a$ was considerably weakened by 59%, which would accelerate the de-bonding process of fibres and in turn impair the fibre bridging effect (Nematollahi et al., 2017b). Similarly, because of the better interface properties, the mixture made from NaOH and Na$_2$SiO$_3$ had the highest tensile strength and strain capacity of 4.7 MPa and 4.3% compared to those activated by NaOH, KOH and K$_2$SiO$_3$, and Ca(OH)$_2$ and Na$_2$SiO$_3$ (Nematollahi et al., 2015). 20% was regarded as the optimal content of sodium metasilicate pentahydrate powder considering the tensile properties of EGCs (Nguyễn et al., 2021). As mentioned previously, increasing the content of sodium metasilicate pentahydrate powder can induce better interface properties for the EGC, while the excessive addition would impair the fibre bridging capacity as the extraordinary interface behaviour can increase the possibility of fibre rupture. The tensile properties can be also affected by the concentration of NaOH solution. Changing the molarity of NaOH solution from 8 M to 12 M did not lead to a significant variation in the tensile properties.
of FA-based EGCs reinforced with both PVA and steel fibres (Farooq et al., 2019). However, a different finding was reported that increasing the molarity of NaOH solution up to 14 M resulted in a higher tensile strength for the EGC due to the accelerated reaction process mentioned in Section 2.4.1 (Cai et al., 2022). It should be noted that the tensile strain capacity dropped with the increase of NaOH concentration due to the decreased $J_b$ (Cai et al., 2022). Additionally, the molarity of NaOH solution should be controlled as excessive OH⁻ would diminish the strength of EGCs (Zahid et al., 2020).

As stated earlier, the inclusion of aggregate is detrimental to the tensile strain capacity of EGCs. As expected, independent of the used ingredient for the matrix, increasing the sand content generally increased the tensile strength of EGCs but weakened the tensile strain capacity (Nematollahi et al., 2016, Yoo et al., 2022, Kumar et al., 2022, Alrefaei and Dai, 2018). For instance, raising Agg/b from 0.5 to 1.0 decreased the tensile strain capacity of the PVA fibre reinforced EGC from 3.20% to 0.92% (Farooq et al., 2019). Although the matrix of the EGC containing coarse sand had a lower $K_m$ than that with fine sand (Section 2.3.2.1), the tensile properties were still about 22-64% smaller (Nematollahi et al., 2016). This can be ascribed to the poorer interface properties when coarser sand was used. To enhance the sustainability of EGCs, other types of aggregates were adopted to replace the commonly used sand partially or fully. By incorporating expanded glass, ceramic microsphere and expanded perlite as aggregates in EGCs, both tensile strength and strain capacity of EGCs were not improved as compared to the mixture prepared with silica sand (Nematollahi et al., 2017c). Applying 40% copper slag to replace silica sand led to a 46% and 59% rise in the tensile strength and strain capacity of the EGC, respectively (Yaswanth et al., 2022a). Crumb rubber was also added into the EGC as aggregate to reduce $K_m$, which can improve the multiple cracking behaviour via introducing more active flaws (Li, 2019). As shown in Figure 2-9c, the presence of a certain content of crumb rubber can lead to better tensile strain capacity while maintaining adequate tensile strength for the EGC (Lương et al., 2021).

As aforementioned, defoamers were used to avoid the formation of unintentional large pores whilst the manufacturing process and the effect of their contents was presented in Ref. (Lee et al., 2017), indicating that the addition of 1% and 2% defoamer can increase the tensile strength and tensile strain capacity of EGCs by 26-27% and 11-23%, respectively. Normally, the reduced porosity induced by the use of a
defoamer could improve $K_m$ and thereby weakening the tensile strain capacity. However, the defoamer would result in increasing interface properties and thus better fibre bridging behaviour as well as higher strain capacity. This is consistent with the previous discussion in Section 2.3.3 that the interface behaviour can affect the strain-hardening indices more significantly compared to $K_m$.

Irrespective of fibre type, several studies illustrated that increasing the fibre content consistently improved the tensile properties of EGCs (Al-Majidi et al., 2017, Nguyen et al., 2018, Farooq et al., 2019). Although other types of fibre were also used to fabricate EGCs, the resultant tensile strain capacity was typically less than 0.5%, as demonstrated in Figure 2-10c (Farooq et al., 2019, Lao et al., 2022, Alrefaei and Dai, 2018). The unimproved tensile strain capacity was mainly due to insufficient fibre bridging behaviour. For instance, the number of steel fibres crossing a certain area is significantly lower compared to that of PVA fibres due to the larger diameter of steel fibres, reducing the fibre bridging efficiency. Nevertheless, the tensile strength of steel fibre reinforced EGCs was 11-88% higher than that of PVA or PE fibre reinforced EGCs (Farooq et al., 2019, Alrefaei and Dai, 2018). Regardless of binder type, partial replacement of PE fibres with steel fibres up to 0.5% was feasible to maintain the acceptable tensile behaviour for EGCs (Alrefaei and Dai, 2018). The aspect ratio of the fibre can also affect the tensile properties of EGCs, where the mixtures possessed higher tensile properties when the reinforcing fibre had a higher aspect ratio (Farooq et al., 2022, Zahid et al., 2020, Choi et al., 2021), which can be mainly ascribed to the better fibre bridging stress when the fibre has a higher aspect ratio.

It was noticed that heat curing impaired the tensile strength of EGCs but improved the tensile strain capacity due to the existence of more flaws induced by shrinkage cracking (Farooq et al., 2022), while it was observed that both tensile parameters of the FA-based EGC were improved when heat curing was used (Ohno and Li, 2014). Regarding the effect of the curing time, the tensile strength and strain capacity of the GGBS-based EGC were found to stop rising after 7 d (Choi et al., 2019a), which can be attributed to the high reactivity of GGBS in the early ages. Differently, increasing the curing period from 3 d to 7 d and 28 d, the tensile strength of the FA-MK based EGC did not change considerably, while its tensile strain capacity was decreased by 6% and 24%, respectively (Kan et al., 2020a). The different trends for these two EGC types can be explained by their disparate reaction mechanism and products.
Figure 2-11 illustrates the fibre bridging behaviour of EGCs under uniaxial tension. Given that the pre-existing pore is not bridged by the fibre (see the microscopic image), the first crack typically initiates from the largest pore inside the specimen. As the tensile load increases, the crack would propagate along the weakest zone (e.g., interface between paste and aggregate) and the fibres at the interface start bridging it. It should be noted that fibres are regarded as 2D randomly distributed inside the dog-bone shaped specimen (Yu et al., 2018), which can have different embedment lengths and inclination angles. The complete fibre pull-out behaviour would contribute to the improved fibre bridging capacity while ruptured fibres can impair it. For the identical matrix, the interface properties are comparable while the different fibre failure modes can be caused by the distinct embedment lengths and more importantly the disparate inclination angles. Besides, if the interface properties are too high, the fibres would be more easily damaged when passing through the rough matrix and thus causing the fibre rupture (Li, 2019). At the cracking interface, the fibres with longer embedment lengths can improve the fibre bridging behaviour given that the length is lower than the critical value (Zhu et al., 2022). However, the fibres with higher inclination angles would impair the fibre bridging performance since they tend to rupture as a result of reduced fibre strength. The reduction in fibre strength is induced by fibre surface abrasion, local bending and lateral stress (Li et al., 2021b). Further, the matrix spalling may happen at the exit point, which reduces the effective embedment length and thus diminishes the pull-out resistance (Li, 2019).
Figure 2-11 Schematic illustration of fibre bridging action of EGCs under uniaxial tension (Zhu et al., 2022).

2.4.5.3 Tensile strain energy

Figure 2-12 summarises the available results on the tensile strain energy of EGCs. As expected, the tensile strain energy improves with the increase of tensile strain capacity. In other words, the higher the tensile strain energy, the stronger the strain-hardening performance. Specifically, the tensile strain energy of EGCs ranged from 21.3 kJm$^{-3}$ to 780 kJm$^{-3}$, where the highest one was about 5.3 times higher than that of the normal ECC (Yoo and Banthia, 2022). It should be mentioned that EGC mixtures that can achieve tensile strain energy of over 300 kJm$^{-3}$ are mostly made from GGBS, while there was one produced with FA. However, as mentioned in Section 2.2.1, some drawbacks existed for these types of EGC and FA-GGBS based EGCs hold promises to address those deficiencies. As seen in Figure 2-12, no study has examined the tensile strain energy of FA-GGBS based EGCs, and thus future research is needed.
Figure 2-12 Relation between tensile strain capacity and tensile strain energy for EGCs (data adapted from Refs. (Yoo et al., 2022, Nguyên et al., 2021, Luong et al., 2021, Lee et al., 2017, Choi et al., 2019a, Choi et al., 2021)).

2.4.5.4 Cracking analysis

Analysing the cracking characterises of EGCs can help understand their crack-controlling performance. Figure 2-13 gives an example of the damage evolution in the EGC under tensile loading, indicating that the number of cracks raised with the increasing tensile load along with the reduced crack spacing (Ohno and Li, 2014). This section will mainly focus on the crack spacing and crack width of EGCs.

Figure 2-13 Microcrack development in the EGC with the increase of tensile loading (Ohno and Li, 2014).

The relation between crack spacing and tensile strain capacity of EGCs is presented in Figure 2-14a, where most results of crack spacing were evaluated by dividing the gauge length (typically 80 mm for a dog-bone shaped specimen) by the number of cracks (Zhao et al., 2021b). A prominent trend can be found that the higher the tensile
strain capacity, the lower the crack spacing. The range of crack spacing for EGCs was wide, from only 0.56 mm to 29 mm. Mostly, the crack spacing was lower than 8.6 mm when the tensile strain capacity was higher than 2%.

Figure 2-14b shows the relationship between crack width and tensile strain capacity of EGCs. Herein, ‘R’ means the residual crack width, which can be measured using a digital microscope. ‘L’ denotes the crack width mainly determined by dividing the highest tensile deformation by the number of cracks (Zhao et al., 2021b). Both methods can be regarded as indirect approaches to assessing the crack width of EGCs and the obtained results would be smaller than those under the actual loading (Li et al., 2001). Generally, it can be found that irrespective of residual or loaded crack width, the crack width tends to reduce with the increase of tensile strain capacity. Nevertheless, there was no significant change in crack width at a higher tensile strain capacity (over 10%) (Nguyễn et al., 2021). The crack width of EGCs was in the range of 20.2-229.2 µm, and more than 73% of the results were less than 100 µm which was similar to the crack width of a typical ECC (Li et al., 2001). These tight crack widths can offer benefits to the self-healing and durability of EGCs (Qiu et al., 2016), which will be discussed in Sections 2.4.9 and 2.5.

Figure 2-14 Relations between tensile strain capacity and (a) crack spacing and (b) crack width for EGCs (data adapted from Refs. (Nematollahi et al., 2016, Lee et al., 2017, Alrefaei and Dai, 2018, Choi et al., 2019b, Choi et al., 2019a, Kan et al., 2020b, Zhao et al., 2021b, Choi et al., 2021, Luong et al., 2021, Kan et al., 2021, Nguyễn et al., 2021, Lee et al., 2012, Nematollahi et al., 2015, Zhang et al., 2020c, Li et al., 2021a, Yaswanth et al., 2022a)).

*Note: R = residual crack width, L = loaded crack width.*
2.4.6 Flexural behaviour

As seen in Figure 2-15, in addition to deflection-hardening behaviour, multiple cracking can be observed for EGCs. Under flexural loading, a crack can be induced locally at the weakest zone, while the fibres at the interface bridge it, sustaining and transferring the stress. Whist the crack opens continuously, and the fibres undergo the pull-out process, additional microcracks would be generated. Similar to uniaxial tension, fibre pull-out is favourable for improving the deflection-hardening behaviour whereas fibre rupture can weaken it. Until now, limited studies have characterised the flexural strength of EGCs using the four-point bending test, the results of which are presented in Figure 2-16. A general trend can be observed that the flexural strength grows with compressive strength, ranging from approximately 4 MPa to 33 MPa. The flexural behaviour of EGCs can be influenced by the aggregate size and content, NaOH concentration and more importantly, fibre type and dosage. Most of the studied mixtures can possess a pronounced deflection-hardening feature.

![Figure 2-15 Typical flexural behaviour and failure pattern of EGCs](Lee et al., 2012, Wang et al., 2021b).

The changing trend of flexural strength with the molarity of NaOH solution (6-14 M) was consistent with that of compressive strength, where the highest flexural strength was attained when the used molarity was 12 M (Cai et al., 2021). Nevertheless, the ultimate deflection of the EGC was generally reduced with the increasing NaOH concentration, which can be ascribed to the increased $K_m$, similar to the reason for the reduced tensile strain capacity (Cai et al., 2022).
The inclusion of silica sand improved the flexural strength, deflection and toughness of EGCs by 17-38%, 2.5-13% and 44-94%, respectively, and the optimal Agg/b was found to be 0.2 (Wang et al., 2021b). Similar results were reported in Ref. (Shaikh, 2013) that the flexural strengths of EGCs with steel or PVA fibres were enhanced by 31% and 6.9% respectively when the content of sand with a smaller size (0.6 mm) increased from 0.5 to 0.75, while no improvement was found when the used sand had a larger size (1.18 mm). There was no clear trend in terms of flexural deflection and toughness when either sand size or sand content changed. Like compressive and tensile strengths, using 40% copper slag to replace silica sand resulted in the highest flexural strength for the EGC, mainly due to the formation of ferrosialates induced by the reaction between alkaline activator and iron oxide from the copper slag (Yaswanth et al., 2022a).

Due to the higher stiffness of steel fibres, the mixtures with steel fibres outperformed the PVA fibre reinforced mixtures in terms of flexural strength (51-98% higher) (Shaikh, 2013). While the low stiffness of PVA fibres was more beneficial for the flexural deflection of EGCs. The mixtures with hybrid steel and PVA fibres (1.0% + 1.0%) exhibited lower flexural strengths than steel fibre reinforced EGCs but higher compared to PVA fibre reinforced EGCs. However, opposite results were also reported in terms of the flexural properties of EGCs with steel or PVA fibres (Al-Majidi et al.,...
Replacing 0.25-0.5% PVA fibre with RTS fibres did not improve the flexural strength and deflection of the PVA fibre reinforced EGC, while their flexural toughness was comparable (Wang et al., 2020), which can be ascribed to the irregular geometrical characteristics of RTS fibres, similar to that contributing to the reduced workability (Section 2.4.1).

It is worth mentioning that the mixture showing deflection-hardening behaviour may not mean it would possess strain-hardening behaviour under uniaxial tension (Li, 2019) and therefore, very limited studies have conducted the bending test to investigate the tensile behaviour of EGCs.

2.4.7 Dynamic mechanical behaviour

Traditional reinforced concrete structures may be susceptible to various extreme loading conditions (e.g., impact and blast) owing to the brittleness of the plain concrete as well as its weak energy absorption capacity (Yoo and Banthia, 2019). As shown in Figure 2-17, these extreme conditions have higher strain rates ranging from $10^{-1}$ to $10^{3}$ s$^{-1}$ and are dynamic, while the mechanical properties discussed in the last several sections belong to quasi-static loading regimes. To improve the resistance of concrete structures against various extreme loading conditions, utilising EGCs as part of these structures is a promising option.

![Figure 2-17 Typical strain rates and corresponding loading conditions (Kim et al., 2009).](image)

To date, only a very few studies have examined the dynamic mechanical properties of EGCs and various test methods were employed including direct tensile test (Farooq et al., 2022), low-velocity drop weight test (Cai et al., 2022, Cai et al., 2021), and split Hopkinson tension bar test (Trindade et al., 2020). The strain rate that can be achieved during the direct tensile test is normally less than 1 s$^{-1}$ (Farooq et al., 2022), while using the last one can get higher strain rates (over 10 s$^{-1}$) (Yoo and Banthia, 2019). Similar to ordinary concrete, a remarkable strain rate effect can be observed in EGCs that the dynamic tensile strength went up with the rising strain rate (see Figure 2-18) (Farooq et al., 2022). A parameter called DIF can be used to quantify it. However, the
tensile ductility exhibited a downward trend with the increase of strain rate, which can be ascribed to the increased interface properties especially $G_d$ (Li, 2019, Farooq et al., 2022, Trindade et al., 2020). Thus, more fibres may be ruptured, leading to reduced fibre bridging behaviour and thereby the ductility is weakened. Such explanation is not valid for all studied EGC mixtures as one study observed more pulled out PVA fibres under dynamic loading due to improved fibre properties (Trindade et al., 2020). Besides the fibre and interface properties, the fibre embedment length and inclination angle can also affect the fibre failure mode. Given the reduced ductility, most EGC mixtures lost their strain-hardening and multiple cracking features under dynamic tensile loading and even some mixes showed a single crack localisation.

Figure 2-18 Effects of curing condition and strain rate on tensile stress-strain response of EGCs and fibre failure mode at the crack interface (Farooq et al., 2022).

Apart from the strain rate effect, the dynamic mechanical properties of EGCs can be also affected by the matrix composition, fibre and curing regime. Regardless of curing condition, the dynamic tensile strength of FA-GGBS based EGCs was higher than that of FA- and GGBS-based EGCs at a strain rate of around 0.5 s$^{-1}$ (Farooq et al., 2022). Similar to the quasi-static mechanical properties, increasing the fibre aspect ratio from 130 to 200 resulted in a 7-37% rise in the dynamic tensile strength of EGCs. Given that heat curing can induce more shrinkage cracks, most heat-cured EGCs exhibited a higher tensile strain capacity but lower tensile strength than ambient-cured EGCs under dynamic loading. Besides, all EGCs with heat curing exhibited ductile failure rather than brittle failure as observed in most ambient-cured EGCs. The strain at fracture localisation of the EGC with PE fibres was about 44% larger than that of
the PVA fibre reinforced EGC at a strain rate of about 300 s\(^{-1}\), which can be ascribed to the higher crack density (Trindade et al., 2020). This can be also explained by their bond strengths under dynamic loading. As mentioned previously, the interface properties especially \(G_d\) of EGCs with PVA fibres can be enhanced with the increasing strain rate, which would impair the bond strength. By contrast, only \(\tau_0\) of PE fibre reinforced EGCs would be improved as it does not possess \(G_d\), which is beneficial to the bond strength. These can be supported by Figure 2-19 that more residual particles remained on the surfaces of PVA fibres while no obvious attached particles can be observed for PE fibres. Owing to the smaller diameter and larger collective embedment surface of PE fibres, EGCs with PE fibres should exhibit a higher dynamic tensile strength than PVA fibre reinforced EGCs. Nevertheless, the experimental results in Ref. (Trindade et al., 2020) did not illustrate such phenomenon, which could be associated with the dynamic tensile strength of PE fibres. Based on the impact performance of EGCs after subjecting to a drooping hammer with various heights (100-800 mm), it was found that the threshold NaOH molarity for EGCs was 12 M as the impact energy dropped when the used NaOH molarity altered from 12 M to 14 M (Cai et al., 2022).

![Figure 2-19 Fracture surfaces of EGCs with PVA or PE fibres under quasi-static and dynamic conditions](image)

**2.4.8 Bond behaviour**

The bond between the EGC and the reinforcement can affect the mechanical behaviour of reinforced concrete structures, which has been rarely studied. Independent of FA/GGBS ratio, all FA-GGBS based EGCs outperformed FA-based EGCs in terms of bond strength because of the increased contact surface between the
EGC and the steel rebar caused by the reduced porosity (Ling et al., 2019). In particular, using 20% GGBS to replace FA in the EGC can lead to the highest bond strength (6.2 MPa) among other mixtures. The bond strength of the EGC was consistently improved with the increasing Agg/b (0.3-1.0) (Kumar et al., 2022). Besides, it was reported that the failure between the EGC and the steel rebar followed a frictional pull-out mode, instead of the splitting failure mode observed between normal concrete and steel rebar. In general, the bond behaviour can be affected by the characteristics of EGCs including mechanical properties and microstructure, diameter and embedment length of steel rebar, and thickness of concrete cover (Ling et al., 2019).

2.4.9 Self-healing behaviour

The use of ECCs for concrete structures can enhance the self-healing efficiency owing to the tight crack width and low W/b of ECCs (Li, 2019). The self-healing efficiency of ECCs reduces with the increasing crack width, where it would be difficult for the crack to heal if its width is larger than 150 µm (Yang et al., 2009). As discussed in Section 2.4.5.4, most EGC mixes had an average crack width of lower than 100 µm implying large self-healing potentials.

The self-healing ability of EGCs is not only affected by their material composition but also the exposure condition. Water was the common exposure environment for estimating the self-healing of EGCs (Nguyen et al., 2018, Nguyen et al., 2019b, Nguyen et al., 2019a), while other exposure conditions (e.g., air and wet-dry cycles) were rarely considered (Kan et al., 2019). Figure 2-20 displays an example of the GGBS-based EGC in terms of its crack width change with the water exposure time, revealing that the crack was fully healed after 36 d of water exposure. Compared to the EGC, the ECC has relatively superior self-healing behaviour with a 14% higher resonant frequency recovery, which can be attributed to the smaller initial crack width of the ECC (Nguyen et al., 2018). Using Ca(OH)₂ as the activator can induce the best self-healing performance for the EGC in comparison with that activated by NaOH or Na₂SiO₃, while the mixture made with Na₂SiO₃ did not present a pronounced self-healing behaviour (Nguyen et al., 2019b). The mechanical properties of EGCs after the self-healing of cracks can also reflect the self-healing efficiency, which have not been considered in the above studies. Figure 2-21 illustrates the effects of exposure environment and preload tensile strain level on the tensile strength and strain capacity of FA-MK based EGCs (Kan et al., 2019), where 0% preload tensile strain means that the EGC specimen was not preloaded but exposed to the same environment. The
changing tendency of tensile properties with the preload tensile strain level was not clear, while it seems that air exposure can lead to better self-healing behaviour for the EGC as opposed to the exposure of wet-dry cycles (Kan et al., 2019). In particular, after 7 d of air exposure, the mixture exhibited a tensile strength of 3.3 MPa along with a tensile strain capacity of 6.13%, which surpassed the mixture without preloading.

![Figure 2-20 Variation of crack width of the EGC at various water exposure ages (Nguyen et al., 2018).](image1)

![Figure 2-21 Tensile properties of EGCs under various exposure conditions and preload tensile strain levels (Kan et al., 2019).](image2)

The continuous reaction of unreacted particles can be regarded as the main mechanism of self-healing in EGCs, and the healing products vary with the change in material composition. For the low-calcium (FA-MK based) EGC system, amorphous aluminosilicate phases were the main healing products (Kan et al., 2019). By contrast, the healing products in the high-calcium system were similar to those in ECCs, e.g., calcium carbonate (Nguyen et al., 2019b, Nguyen et al., 2019a, Nguyen et al., 2018).

2.5 Durability of EGCs

Cementitious materials can experience degradation under various environmental loads (e.g., freeze-thaw cycles) and attacks of aggressive agents (e.g., chloride ions) (Ranjbar and Zhang, 2020). Due to the tight crack width of EGCs, their permeability
can be much lower as opposed to similarly strained concrete, which would be beneficial to the durability of concrete structures made up of EGCs (Li, 2019).

2.5.1 Fire/thermal resistance

In service, concrete structures would be subjected to fire attack, where the high temperature would not only cause the deterioration of concrete but may also induce the spalling of concrete and thereby expose the reinforcing bar to the fire flame (Ma et al., 2015). The commonly used PVA and PE fibres in EGCs with low melting points (140-240 °C) have the potential to improve the resistance to spalling as they can mitigate the inner vapour pressure by leaving empty channels after melting to increase pore connectivity and permeability (Wu et al., 2020).

A study on the effects of NaOH concentration (6-14 M) and temperature (50 °C, 100 °C and 150 °C) on the impact behaviour of MK-based EGCs indicated that the impact force and energy of the EGC were improved with the increasing temperature due to the enhanced bonding between fibre and matrix as a result of the formation of more reaction products (Cai et al., 2021). By contrast, the impact behaviour of the ECC showed an opposite trend. At a lower temperature (50 °C), the ECC outperformed the EGC in terms of impact behaviour while as the temperature raised to 100 °C and 150 °C, EGCs exhibited better performance. The concentration of NaOH should not exceed 12 M at a higher temperature (100 °C and 150 °C). The flexural strengths of EGCs with PVA and PE fibres were about 6-51% and 20-57% lower as the exposure temperature went up, due to the loss of chemically and physically bonded water and the damage to fibres (Constâncio Trindade et al., 2022). Herein, some samples were tested after heating immediately while the rest were tested after experiencing a cooling period. Regardless of fibre type, the strength loss of EGCs after the first regime was greater than that after the second regime, which can be ascribed to the increased fibre elongation and fibre stiffness recovery following the rapid cooling process. When the temperature changed to 200 °C, the mixture with PE fibres yielded a lower residual flexural strength than the PVA fibre reinforced EGC, mainly due to the lower melting point of PE fibres (150 °C). As PVA fibres have a higher melting point (240 °C), they do not suffer any obvious degradation at 100 °C and only slight damage at 200 °C.

The compressive strength of the FA-GGBS based EGC with 2.0% PVA fibre was improved by 34% and 29% when the exposure temperature increased from 20 °C to 105 °C and 250 °C, due to the further reaction of unreacted FA particles under a certain high temperature (Chan and Zhang, 2022), which was also approved in Ref. (Humur...
and Çevik, 2022b). However, a further rise of temperature to 400-800 °C significantly weakened the compressive strength of the EGC, due to an increase in microcracking and porosity induced by the loss of water and melted PVA fibres as well as the dehydration of reaction products (Park et al., 2016). For the GGBS-based EGC, a consistent downward trend in compressive strength can be observed, which can be attributed to the rise in vapour pressure and internal cracking as a result of its dense microstructure (Humur and Çevik, 2022b). Figure 2-22 presents the effect of elevated temperature on the tensile behaviour of EGCs, indicating the pronounced tensile strain-hardening and multiple cracking features of EGCs under various temperatures, which is consistent with the results of compressive strength (Chan and Zhang, 2022). When the temperature was higher (400-800 °C), all EGCs did not exhibit strain-hardening behaviour with only one major crack. As seen in Figure 2-22b, the tensile strength and tensile strain capacity mostly followed a similar change trend of compressive strength with elevated temperature, which can be explained more clearly using the microscopic images (Figure 2-23). At 105 °C, no noticeable damage can be found on PVA fibres while the fibres melted and shrunk at 250 °C. At 400 °C, only slight residuals of PVA fibres can be identified, which significantly weakened the fibre bridging effect and thereby reduced the tensile behaviour of the EGC especially tensile strain capacity.

Figure 2-22 Effect of elevated temperature on (a) tensile stress-strain response, and (b) tensile strength and tensile strain capacity of EGCs (data adapted from Refs. (Chan and Zhang, 2022, Humur and Çevik, 2022b)).
2.5.2 Chemical resistance

In recent years, the resistance of EGCs to sulphate attack and ingress of chloride ions has been studied. In Ref. (Salami et al., 2017), POFA-based EGC specimens were exposed to three different sulphate solutions including 5% Na$_2$SO$_4$, 5% MgSO$_4$ and a combination of 2.5% Na$_2$SO$_4$ and 2.5% MgSO$_4$ for 3-9 months. It was found that regardless of the used NaOH concentration (10 M, 12 M and 14 M) and type of sulphate solution, all mixes experienced a conspicuous loss in compressive strength after different periods of exposure. In particular, the samples after exposure to 5% Na$_2$SO$_4$ had the highest strength loss, while the mixtures after exposure to 5% MgSO$_4$ exhibited the least loss in strength. The strength loss of EGC samples was strongly associated with the molarity of NaOH solution due to the loss of a high amount of reaction products induced by depolymerisation at a higher NaOH concentration. The experimental study on the resistance of GGBS-RHA based EGCs with different contents of copper slag to sulphate and seawater attacks indicated that irrespective of copper slag replacement level to silica sand, all specimens had excellent resistance to seawater as compared to sulphate attack, considering the loss in compressive strength (Yaswanth et al., 2022a). Consistent with mechanical properties, employing 40% copper slag to substitute silica sand resulted in the least strength loss. For instance, after 90 d of exposure to sulphate solution, only 3.8% strength loss was observed for
the mixture with 40% copper slag, while 7.7% was found for that containing 60% copper slag owing to its looser microstructure. The microstructural investigation indicated no harmful chemical elements in EGCs under these aggressive environments. Similar superior resistance was found for the mixture with a 40% replacement level of copper slag under rapid chloride penetration (Yaswanth et al., 2022b).

2.6. Summary

This chapter comprehensively reviewed the state-of-the-art of EGCs, specifically in terms of mix design, manufacturing process and essential material properties, and discussed the relations between key mechanical properties. Some important conclusions can be drawn:

- Adopting the micromechanical design theory, EGCs with pronounced strain-hardening and multiple cracking features can be developed and their uniaxial tensile behaviour can be tailored by adjusting the material composition (e.g., precursor type, activator nature and fibre content) that would modify its microstructure and in turn change the properties of matrix and fibre-matrix interface.

- The tensile properties of most EGCs have a positive correlation with the strain-hardening indices, where the index values are higher when a stronger frictional bond and a lower slip-hardening coefficient are present at the interface. In comparison with the widely used ECC (M45), most EGC mixes exhibit a lower matrix fracture toughness and interface properties.

- The commonly used precursor, activator, aggregate and fibre in EGCs are fly ash, a mixture of NaOH and Na₂SiO₃, silica sand with a size of less than 1180 µm and content of 20-50% (by binder mass), PVA or PE fibres with volume fraction of no higher than 2.0%, respectively.

- The tensile strength of most EGC mixes has positive correlations with compressive strength and tensile strain capacity. The crack spacing and crack width are reduced with the increasing tensile strain capacity. In comparison with M45 ECC, approximately 29% of EGC mixtures exhibit a higher tensile strength (> 4.86 MPa), while about 66% of mixes have a higher tensile strain capacity (> 2.49%). Around 37% of EGC mixes have compressive strength ranging from 40 MPa to 70 MPa, which is adequate for most structural applications.
• The self-healing of EGCs can be triggered by the reaction of unreacted particles and the type of healing products is dependent on the used precursor and activator. The tensile properties of cracked EGCs after air exposure are higher than that of mixtures after exposure to wet-dry cycles.

• EGCs with PE fibres exhibit better tensile behaviour than those with PVA fibres under both static and dynamic loadings, while the lower melting point of PE fibres brings concerns to the fire/thermal performance of EGCs, especially at a temperature over 200 °C.

Some main challenges and limitations in this research field are summarised as follows:

• PVA or PE fibres have been mainly utilised in EGCs, which is not eco-friendly considering their material cost and potential environmental impact. Although other kinds of fibres with relatively lower material cost (e.g., PP fibres) were used to develop EGCs, their tensile strain capacity was very limited (typically no more than 0.5%). To improve the sustainability of EGCs while retaining acceptable engineering properties, partially replacing PVA fibres with recycled fibres is a promising approach.

• RTP fibres from waste tyres have a great potential to be the partial replacement of PVA fibres in EGCs due to their positive influences on the shrinkage resistance, fire resistance, fatigue behaviour, and dynamic mechanical behaviour of cement-based concrete. However, the feasibility of incorporating RTP fibres in EGCs has not been explored.

• EGCs made with blended FA and GGBS have been increasingly studied as they not only can mitigate the drawbacks of FA-based and GGBS-based EGCs, but also present superior engineering properties under ambient temperature. Up to now, the static mechanical properties of FA-GGBS based EGCs have been extensively studied. Nevertheless, their dynamic mechanical properties have been rarely explored, which would limit the widespread application of EGCs. Limited strain rates were considered among the existing studies on dynamic mechanical properties of EGCs, which cannot develop a reliable model describing the relationship between DIF and strain rate.
Chapter 3 Engineering properties of EGCs

3.1 Introduction

Except for uniaxial tensile behaviour, engineering properties covering fresh and hardened properties are also crucial for the engineering application of EGCs. Therefore, the main purpose of this chapter is to understand the effects of various PVA fibre contents and RTP fibre replacement dosages on the workability, setting time, drying shrinkage, compressive strength, elastic modulus, and splitting tensile strength of EGCs. Additionally, the material cost, embodied carbon and embodied energy of EGCs are assessed as well. It should be noted that most of the experiments presented in the following chapters were done at a laboratory of Northeastern University in China. Part of this chapter has been presented in the following peer-reviewed journal paper: Zhong, H. & Zhang, M. (2021) Effect of recycled tyre polymer fibre on engineering properties of sustainable strain hardening geopolymer composites. Cement and Concrete Composites 122:104167.

3.2 Experimental program

3.2.1 Raw materials

Low-calcium FA as per ASTM C618-17a (2017) and GGBS with a hydration modulus (i.e. the ratio of CaO + MgO + Al₂O₃ to SiO₂) of 2.0 were used as precursors in this study, the chemical composition of which is given in Table 3-1. It is worth noting that the hydration modulus of GGBS should be higher than 1.4 to ensure good hydration characteristics (Chang, 2003). The apparent morphologies of FA and GGBS are shown in Figure 3-1, indicating that the shape of FA particles is spherical while GGBS particles are mostly angular. Figure 3-2 presents the particle size distribution of FA and GGBS, where their average particle sizes are 19.58 µm and 9.78 µm, respectively. Figure 3-3 illustrates the X-ray diffraction (XRD) patterns of FA and GGBS measured using a Malvern Panalytical X’Pert³ Powder diffractometer, where CuKα X-ray was employed at 45 kV and 40 mA and 2θ configuration ranging from 5-70° was applied. It can be observed that FA consists of a considerable amount of amorphous phases (board hump range of 2θ=15°-35°) and its major crystalline phases are mullite and quartz. A significant amount of amorphous phases can also be detected for GGBS, as seen in the board hump from 2θ=25° to 2θ=35°.
Table 3-1 Chemical composition (wt.%) of FA and GGBS.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>SO₃</th>
<th>MgO</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>Loss on Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA</td>
<td>57.02</td>
<td>32.35</td>
<td>3.01</td>
<td>2.88</td>
<td>0.41</td>
<td>0.58</td>
<td>1.26</td>
<td>0.20</td>
<td>2.45</td>
</tr>
<tr>
<td>GGBS</td>
<td>31.85</td>
<td>17.31</td>
<td>0.34</td>
<td>41.20</td>
<td>1.78</td>
<td>6.13</td>
<td>0.62</td>
<td>0.02</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Figure 3-1 SEM images of (a) FA and (b) GGBS.

Figure 3-2 Particle size distribution of (a) FA and (b) GGBS.

Figure 3-3 XRD pattern of FA and GGBS.
To control the fracture toughness of the geopolymer matrix, fine silica sand with a maximum particle size of 250 µm and an average particle size of 130 µm was utilised as fine aggregate. A combination of 10 M NaOH solution and Na$_2$SiO$_3$ solution with a silicate modulus (SiO$_2$/Na$_2$O) of 3.15 was used as the alkaline activator. To improve the flowability of fresh EGC samples, a modified polycarboxylate-based SP (Sika®ViscoFlow®3000) was applied. Table 3-2 lists the specific gravity of the above raw materials.

Table 3-2 Specific gravity of different ingredients (except fibres) in EGCs.

<table>
<thead>
<tr>
<th></th>
<th>FA</th>
<th>GGBS</th>
<th>Silica sand</th>
<th>NaOH</th>
<th>Na$_2$SiO$_3$</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.19</td>
<td>2.90</td>
<td>2.66</td>
<td>1.31</td>
<td>1.38</td>
<td>1.06</td>
</tr>
</tbody>
</table>

PVA fibres (Kuraray Co., Ltd., Japan) and RTP fibres from waste tyres were used as fibre reinforcements in this study. Since many rubber particles attach to the RTP fibres, a sieving/cleaning process based on a previous study (Baričević et al., 2018) proceeded on the as-received RTP fibres before usage. The schematic illustration of the cleaning process is shown in Figure 3-4. Firstly, three sieves with different openings (0.315 mm, 0.63 mm and 1.25 mm) were placed on the vibration table. Then, a certain amount of as-received RTP fibres was placed in the sieve with an opening of 1.25 mm and it should be noted that several rubber balls were adopted to improve the efficiency of removing the rubber particles. Because of the gravitational forces, very fine RTP fibres and rubber particles fell into the bottom sieves or the tray. The shaking time was about 10 min. Afterwards, a small-scale fan was applied to spin the RTP fibres in the 1.25 mm-sieve whilst shaking, which can force the impurities to fall to the bottom. Around 10 min was required for this procedure.

Figure 3-5 illustrates the physical appearance of PVA and RTP fibres (after processed) using various image-capturing instruments including digital camera, portable digital microscope and SEM equipment. Given that RTP fibres may contain different organic compositions, attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) was applied as it is considered as a fast, suitable, non-destructive and inexpensive method for fibre identification (Vahur et al., 2009). As previous studies (Serdar et al., 2015, Chen et al., 2019) found that the primary composition of RTP fibres is PET, the ATR-FTIR method was applied on both RTP and PET fibres using a Nicolet iS10 FT-IR spectrometer with an ATR accessory as per ASTM E1252-98 (2013) to investigate the primary composition of RTP fibres.
Figure 3-4 Schematic illustration of the cleaning process for RTP fibres.

Figure 3-6 presents the FTIR spectra of RTP and PET fibres, indicating that the spectrum of RTP fibre mostly matched that of PET fibre considering various characteristic peak positions within a range of wavenumber. The main peaks (Cole et al., 2002, Meng et al., 2018, Guo et al., 2016, Mecozzi and Nisini, 2019, Atkinson et al., 2000) for PET fibre were highlighted and marked in Figure 3-6. For instance, the peak at 2968.51 cm\(^{-1}\) was related to the stretching vibration of methylene group (-CH\(_2\)) while the significant peak at 1713.17 cm\(^{-1}\) can be attributed to the stretching vibration of carbonyl group (C=O). In addition, the peak at 722.92 cm\(^{-1}\) was corresponding to the out-of-plane bending vibration of the CH on benzene ring. Compared to PET fibre, the spectrum of RTP fibre presented similar peaks at 2917.85, 1712.89, 1245.26, 1096.69, 1018.30 and 722.56 cm\(^{-1}\), suggesting that the RTP fibres used in this study are mainly composed of PET. The thermal behaviour of RTP fibres was studied using a simultaneous thermal analyser (NETZSCH STA 409 PC/PG) at a constant heating rate of 10 °C/min from 30-800 °C under nitrogen gas flow of 100 mL/min. The thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) results are shown in Figure 3-7. The melting point of RTP fibres was about 254 °C and they started to decompose at around 409 °C, suggesting that RTP fibres had similar thermal behaviour to that of PET fibre (Zhang and Tan, 2020). As seen in Figure 3-5, the RTP fibres are not uniform in dimension. Thus, a group of RTP fibre samples were
characterised in terms of length and diameter using a digital microscope and a fibre diameter tester (XGD-1 Fibre Diameter Tester), respectively. Figure 3-8 depicts the distribution of length (in mm) and diameter (in µm) of RTP fibres. It can be found that around 87% of RTP fibres are shorter than 8 mm and about 83% of them have a diameter of smaller than 26 µm. Besides, the elongation, tensile strength, and elastic modulus of RTP fibres were measured using a fibre tensile tester (XQ-1A Fibre Tensile Tester). The density of RTP fibres was measured using a gas displacement pycnometry system (AccuPyc II 1345, USA), where helium was used as the displacement medium. During the sieving/cleaning process of as-received RTP fibres, the percentages of RTP fibres and rubber particles (attached with very short RTP fibres) were determined, which were 40% and 60%, respectively. Table 3-3 presents the main properties of PVA and RTP fibres.

Figure 3-5 Physical appearance of (a) PVA fibres and (b) RTP fibres.

Figure 3-6 FTIR spectrum of RTP fibre and PET fibre.
Figure 3-7 TGA and DSC analysis of RTP fibre.

Figure 3-8 Dimension distribution of RTP fibres: (a) length and (b) diameter.

Table 3-3 Main properties of PVA and RTP fibres.

<table>
<thead>
<tr>
<th>Properties/fibre type</th>
<th>PVA</th>
<th>RTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>12.0</td>
<td>5.2 (2.4)</td>
</tr>
<tr>
<td>Diameter (μm)</td>
<td>40.0</td>
<td>21.4 (4.4)</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>6.5</td>
<td>20.6 (2.9)</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>1560</td>
<td>761 (115)</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>41.0</td>
<td>3.8 (0.7)</td>
</tr>
<tr>
<td>Density (kg/m^3)</td>
<td>1300</td>
<td>1476 (3)</td>
</tr>
</tbody>
</table>

Note: the values in parentheses are standard deviations.

3.2.2 Mix proportions

Table 3-4 lists the mix proportions investigated in this study. Regarding the geopolymer matrix, the mass ratios of FA/GGBS, silica sand/binder, activator/binder
and Na$_2$SiO$_3$/NaOH were selected as 4.0, 0.2, 0.45 and 1.5 based on previous studies (Fang et al., 2018, Wang et al., 2021b, Ling et al., 2019, Zhang et al., 2020c). The mass ratio of SP/binder was set as 0.01 as it was reported that adding this content of SP can significantly enhance the workability of FA-GGBS based geopolymer pastes (Jang et al., 2014). These parameters were kept constant and the changing parameters were fibre type and dosage. For the meaning of mixture labels given in Table 3-4, for instance, P1.75R0.25 denotes the geopolymer matrix reinforced with two types of fibres, where ‘P1.75’ stands for the volume fraction of PVA fibre (1.75%) while ‘R0.25’ represents the volume fraction of RTP fibre (0.25%). P0R0 is the reference mixture (no fibre addition). The upper limit of RTP fibre replacement content was set as 1.0% considering that: (1) it would be difficult for EGCs to exhibit strain-hardening behaviour when the content of PVA fibres is less than 1.0% (Jing, 2017); (2) the addition of RTP fibres over 1.0% would not be beneficial to the hardened properties of composites (Chen et al., 2019).

Table 3-4 Mix proportions of all studied mixtures.

<table>
<thead>
<tr>
<th>Mixture label</th>
<th>By weight</th>
<th>By volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FA</td>
<td>GGBS</td>
</tr>
<tr>
<td>P0R0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P1.0R0</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>P1.5R0</td>
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<td>0</td>
</tr>
<tr>
<td>P2.0R0</td>
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<td>0.2</td>
</tr>
<tr>
<td>P1.75R0.25</td>
<td>1.75</td>
<td>0.25</td>
</tr>
<tr>
<td>P1.5R0.5</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>P1.25R0.75</td>
<td>1.25</td>
<td>0.75</td>
</tr>
<tr>
<td>P1.0R1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

3.2.3 Sample preparation

Regarding the sample preparation, the NaOH solution was prepared by mixing NaOH pellets (>99% purity) with tap water, 24 h prior to the mixing process. Herein, 400 g of NaOH pellets were dissolved in the tap water to prepare 1 L of 10 M NaOH solution. All mixtures shown in Table 3-4 were prepared using a 20 L planetary mixer with a constant mixing speed of 140 rpm. Firstly, FA, GGBS and silica sand were dry mixed for 90 s followed by the gradual addition of the alkaline activator. Then, the
mixing was continued for another 180 s before the addition of SPs. Once a consistent mixture was obtained, the PVA fibres were slowly added. It should be mentioned that for the mixtures containing both PVA and RTP fibres, the RTP fibres were first mixed with a certain content of the activator to avoid fibre clumping or balling (Chen et al., 2021a, Onuaguluchi and Banthia, 2017). The mixing process finished when the fibres were uniformly distributed in the mixtures. The total mixing time of all mixtures (except plain geopolymer mixture) was approximately 10 min. A proportion of the fresh mixtures was used for the fresh property test while the remaining was cast in various moulds with sufficient vibration. The samples were sealed by the plastic sheet at ambient temperature (20 ± 2 °C) to avoid moisture loss. After 24 h, the samples (except samples for drying shrinkage test) were de-moulded and cured in a standard curing room (20 ± 2 °C, 95% RH) until desired testing ages.

3.2.4 Test methods

According to ASTM C1437-15 (2015), the flow table test was conducted to assess the workability of fresh mixtures. Firstly, the fresh mixture was poured into a truncated conical mould with a height of 50 mm, a top diameter of 70 mm and a bottom diameter of 100 mm. The spread diameter of each fresh mixture was measured after two steps: (1) lifting the truncated conical mould; (2) tapping the flow table 25 times.

The setting time of EGC mixes was determined by the Vicat setting time test following ASTM C191-19 (2019). A 1-mm Vicat needle was used to penetrate the EGC test sample every 5 min and the penetration depth was recorded. The initial setting time was the time elapsed between the initial contact of raw materials and alkaline activator and the time when the penetration depth was 25 mm. The final setting time was the time elapsed between the initial contact of raw materials and alkaline activator and the time when the needle could not penetrate the sample.

The drying shrinkage test was performed on the 25 mm × 25 mm × 280 mm prismatic specimen with a gauge length of 250 mm. Upon the de-moulding of the specimen, the initial comparator reading of the specimen was taken immediately. Subsequently, the specimen was cured under an environment with a temperature of 20 ± 2 °C and relative humidity of 50% ± 5%. The comparator readings at various curing ages were recorded. The drying shrinkage was determined by comparing the subsequent comparator readings with the initial comparator reading based on ASTM C490-17 (2017).
The uniaxial compression test was conducted on EGC specimens with two different sizes (50 mm cubic (ASTM C109/C109M-20b, 2020) and Ø 100 mm × 200 mm cylindrical samples (ASTM C39/39M-21, 2021)). The adopted loading speeds for the cubic and cylindrical samples were 0.3 MPa/s and 1.0 mm/min, respectively. Before the test, the end surfaces of all cylindrical samples were treated to guarantee their flatness. The measured quasi-static compressive strength based on the cylindrical sample was selected to calculate the DIF to reduce the specimen size and end friction effects (Wang et al., 2011b, Xiao et al., 2015).

Once the average quasi-static compressive strength was obtained, the elastic modulus test was performed according to ASTM C469 (2014). Figure 3-9 shows the setup for the elastic modulus test, where two strain gauges were installed at the mid-height of the tested specimen to measure the longitudinal strain. During the test, the tested specimen was initially loaded to 40% of its ultimate load-carrying capacity based on the average quasi-static compressive strength, followed by an unloading phase and this testing procedure was repeated three times. The corresponding elastic modulus can be calculated as:

\[ E_s = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.00005} \]  

(3-1)

where \( E_s \) is the elastic modulus of the tested specimen, \( \sigma_2 \) is the stress corresponding to 40% of the ultimate stress, \( \sigma_1 \) is the stress at a longitudinal strain of 50 \( \mu \varepsilon \), and \( \varepsilon_2 \) is the longitudinal strain at \( \sigma_2 \).

![Figure 3-9 Experimental setup of elastic modulus test.](image)

The quasi-static splitting tensile test was conducted on the Ø 100 mm × 50 mm cylindrical specimen, which was different from that (Ø 100 mm × 200 mm) specified
by ASTM C496 (2017). The used dimension here was kept consistent with that for the
dynamic splitting tension test to gain reliable DIF values, as indicated in previous
studies (Khan et al., 2019, Chen et al., 2020a). During the test, a vertical load along
the diameter of the tested sample was applied at a constant loading rate of 0.5 mm/min.
Besides, two pieces of plywood were placed between the loading plates and the tested
specimen to avoid stress localisation at the loading point, which can help achieve a
more uniform stress distribution (ASTM C496, 2017).

3.3 Results and discussion

3.3.1 Workability

Figure 3-10a depicts the slump flow of all mixes, which can reflect their
workability. The mixture without any fibre reinforcement (P0R0) had the highest
slump flow of around 250 mm (Figure 3-10b) while regardless of reinforcing fibre
type and dosage, the slump flow of the fresh mixture became lower when fibres were
incorporated, which can be owing to the increased interaction between fibres and
between fibres and other constituent materials and the increased liquid absorption on
the surfaces of fibres (Jiang et al., 2018, Ranbar and Zhang, 2020). Hence, the
movement of the fresh mixture is restricted, increasing the overall shear stress.
Regarding the effect of PVA fibres, the reduction in slump flow caused by the addition
of 1.0% PVA fibre was limited, only 7.3% lower in comparison with P0R0.
Nevertheless, the higher dosages of PVA fibre (1.5% and 2.0%) reduced the
slump flow of the EGC by 19-22%, which is in agreement with previous studies on FA-based
(Farooq et al., 2019) and FA-GGBS based (Wang et al., 2020) EGCs. There exists a
critical fibre dosage, where exceeding it would significantly reduce the workability
of the whole composites and increase the possibility of fibre balling or clumping (Ranbar
and Zhang, 2020). It is suggested that the critical fibre dosage is affected by the fibre
aspect ratio and varies between different fibres, ranging from 0.2-2.0% (by volume)
for geopolymer and cementitious composites (Swamy and Mangat, 1974, Masi et al.,
2015).
Considering the effect of RTP fibres, replacing 0.25% PVA fibre with RTP fibre in the EGC exhibited slightly better workability, implying that a small dosage of RTP fibres would not considerably influence the workability of the EGC. This could be attributed to the smaller aspect ratio of RTP fibres (Masi et al., 2015). However, the slump flow of EGCs containing RTP fibres higher than 0.25% was 8.3-12% smaller than that of P2.0R0. The influence of hybrid fibres on the workability would be different from that of mono-fibre, where the mutual effect between different incorporated fibres could restrict each other’s rotation and thereby affect the fibre orientation to the flow direction of mortar/paste (Yu et al., 2014). The workability of the fresh mixture tends to be further reduced when more fibres align perpendicular to the flow direction of mortar/paste. A congested network may be formed if more RTP fibres with ununiform dimensions are combined with stiffer PVA fibres, resulting in reduced workability for EGCs. Similar findings were also reported in previous studies (Afroughsabet et al., 2018, Zhong and Zhang, 2020) that the workability of hybrid fibre reinforced composites was lower than that of mono-fibre reinforced composites when the fibre replacement dosage exceeded a certain content. P1.0R1.0 exhibited the lowest slump flow of about 171 mm, and thus more vibration would be required for this mixture to increase its compactness inside the mould to avoid a conspicuous loss of hardened properties (Figure 3-10b). It should be noted that no pronounced fibre clumping or balling was observed for all EGC mixtures during the sample preparation.
3.3.2 Setting time

Figure 3-11 presents the effects of PVA and RTP fibre dosage on the setting time of EGCs. As compared with P0R0, the presence of PVA fibres did not significantly vary the initial setting time but decreased the final setting time of EGCs. The final setting time of P2.0R0 was 84 min, about 10% lower than that of P0R0. This could be due to the hydrophilic surface feature of the PVA fibre, absorbing a certain content of alkaline activator during the mixing. It was reported that the consistency of FA-GGBS based pastes was reduced with the decreasing alkaline activator content, resulting in the accelerated reaction of raw materials and thereby lower setting time (Rafeet et al., 2017). A previous study reported a similar phenomenon that increasing the sand content of the EGC shortened its setting time owing to the reduced activator content (Wang et al., 2021b).

Replacing 0.25% PVA fibre with RTP fibre did not lead to an obvious change in both initial and final setting time of the EGC. By contrast, the initial and final setting time of EGCs with RTP fibre content of higher than 0.25% were larger than those of mono-PVA fibre reinforced EGCs. For instance, the initial setting time of P1.25R0.75 was 79 min, which was 23% higher than that of P2.0R0, respectively. This may be attributed to the hydrophobic feature of the RTP fibre that can gradually release some blocked liquid during the drying (Baričević et al., 2018, Serdar et al., 2015). Therefore, the activator content inside these hybrid fibre reinforced EGC mixes was higher compared to that of mono-PVA fibre reinforced EGCs, retarding the chemical reaction and consequently the increase of setting time. According to BS EN 197-1:2011 (2011).
the initial setting time of all EGC mixtures here can fulfil the requirement of engineering application (≥ 60 min).

3.3.3 Drying shrinkage

Due to the high dosage of cement and low volume fraction of fine aggregate, ECCs typically exhibit a very high drying shrinkage, which can promote the initiation of early-age cracking and thereby weaken the long-term durability of concrete structures (Zhang et al., 2009a). It was found that geopolymer matrix generally presents higher shrinkage than cementitious matrix, which is dependent on binder type and activator characteristics (Lee et al., 2014), suggesting that EGCs may pose a larger restraint to the enhancement of durability than ECCs although fibres are incorporated.

Figure 3-12 Effects of PVA and RTP fibre content on drying shrinkage of EGCs.

Figure 3-12 depicts the drying shrinkage of all mixtures up to 28 d, indicating that the drying shrinkage of all mixtures developed rapidly up to 7 d, after which the development of drying shrinkage gradually slowed down. Increasing the PVA fibre dosage consistently decreased the drying shrinkage of the EGC, where the 28-d drying shrinkage strains of P1.0R0, P1.5R0 and P2.0R0 were 11%, 21% and 22% respectively lower than that of P0R0. As the curing age increases, the bonding between PVA fibres and the matrix is improved. Thus, the PVA fibres and fine aggregates can act as a skeleton to increase the dimensional stability of EGCs, reducing the drying shrinkage (Fang et al., 2020). It is noticed that P1.5R0 and P2.0R0 presented a comparable performance in restraining the drying shrinkage of the EGC. Although this is inconsistent with the findings reported in previous studies on geopolymer composites (Ranjbar and Zhang, 2020), a previous study observed that increasing the PVA fibre
volume fraction from 1.5% to 2.0% even reduced the drying shrinkage resistance of the EGC (Wang et al., 2020). As mentioned in Section 3.3.1, the significant decrease in workability for P2.0R0 may entrap more air during the mixing, which would result in a higher internal porosity around the fibres. Therefore, the internal moisture inside the EGC can move more easily through the formed pore network, impairing the shrinkage resistance (Afroughsabet and Teng, 2020).

Figure 3-13 Water contact angle of RTP fibres.

The presence of 0.5% and 1.0% RTP fibre in EGCs improved the drying shrinkage resistance at different extents, where a reduction of 28% in drying shrinkage can be observed after incorporating 1.0% RTP fibre into P1.0R0. Excellent shrinkage-restraining behaviour was also reported for cementitious composites containing RTP fibres (Chen et al., 2021a, Baričević et al., 2018, Serdar et al., 2015), which can be partially attributed to the release of temporarily blocked liquid at the surfaces of RTP fibres caused by their hydrophobicity (Serdar et al., 2015). The hydrophobic behaviour of the RTP fibre can be evidenced by its water contact angle (larger than 130°) shown in Figure 3-13. Although most of the rubber particles attached to RTP fibres were removed after the cleaning process, some tiny rubber particles may still exist which can store some water during the mixing and gradually release as time goes by (Su et al., 2015, Chen et al., 2020b). It is interesting to note that the increase of RTP fibre replacement ratio resulted in a general decreasing trend in drying shrinkage, where the reduction was more pronounced when 0.75% or 1.0% PVA fibre was replaced with RTP fibre. P1.25R0.75 and P1.0R1.0 presented a drying shrinkage of around 10751 µε and 9649 µε at 28 d, which was 7.9% and 17% lower than that of P2.0R0, respectively. The synergistic effect between PVA fibres and RTP fibres is also beneficial to restrain the drying shrinkage via the crack-controlling at two scales. As shown in Table 3-3, PVA fibres have relatively a longer length which helps limit the
propagation of macro-cracks while micro-cracks or tiny internal flaws can be bridged and restrained by the RTP fibres with relatively shorter lengths. Hence, the shrinkage stress across the cracks can be transferred to the bridging fibres, minimising the overall shrinkage. In addition, the fibre bridging effect could prevent or slow down the loss of internal moisture (Gao et al., 2018), which contributes to the reduction of drying shrinkage.

3.3.4 Compressive strength

The presence of fibres can simultaneously exert both positive and negative impacts on the compressive strength of cementitious composites, which are associated with the fibre type and fibre properties, especially stiffness (Yu et al., 2020, Ranjbar and Zhang, 2020). The compressive strength of all mixtures at 28 d is illustrated in Figure 3-14a. The compressive strength of EGC cubic samples containing mono-PVA fibres presented a decreasing trend. In comparison with P0R0, the addition of 1.5% and 2.0% PVA fibre led to a reduction of 14% and 25%, respectively, suggesting that the negative influence caused by the addition of PVA fibres on compressive strength suppressed its positive influence. Regarding the negative influence, the composite has a higher tendency to entrap more air during the mixing because of the reduced workability, which may in turn decrease the compactness of the whole composite, as discussed in Section 3.3.1. Therefore, local fractures tend to occur around the fibres and ultimately weaken the composite’s compressive strength (Ranjbar and Zhang, 2020). The reduced compressive strengths of ECCs caused by the fibre incorporation became more obvious with the reducing W/b, as reported by Yu et al. (2020) who observed a reduction of 14% in compressive strength when 2.0% PVA fibre was added into the plain mixture with a W/b ratio of 0.2. Besides, Wang et al. (2020) found that the compressive strengths of EGCs with 2.0% PVA fibre were 9.7% and 7.3% lower than those containing 1.5% PVA fibre at 7 d and 28 d, respectively. Similarly, the addition of RTP fibres also had a negative impact on the compressive strength of EGCs. For instance, the 28-d compressive strength of P1.5R0.5 was around 45.7 MPa which was 10% lower than that of P1.5R0. Such weakening effect in compressive strength caused by RTP fibres was also found for cementitious composites (Chen et al., 2020b, Chen et al., 2021a), which can be assigned to the weaker fibre-matrix interaction and lower stiffness of RTP fibres. In addition, the rubber granules attaching the RTP fibres may also contribute to the reduction in compressive strength. Nevertheless, in this study, the RTP fibres were pre-treated to remove most of the attached rubber granules,
which would effectively minimise the negative effect due to the rubber granules. Therefore, EGCs containing hybrid PVA and RTP fibres (except P1.25R0.75) exhibited even higher compressive strength (4-9.2% higher) than that with 2.0% PVA fibre, indicating that replacing a certain content of PVA fibres by RTP fibres can help mitigate the loss of compressive strength in the EGC due to the addition of PVA fibres.

Figure 3-14 Compressive strength of EGCs: (a) effects of PVA and RTP fibre content, and (b) examples of compressive failure modes.

Similar to cubic samples, the compressive strength of cylindrical EGC specimens was not improved by adding either PVA or RTP fibres (Figure 3-14a). For instance, the compressive strengths of P1.0R0, P1.5R0 and P2.0R0 were 0.45-7.2% lower than that of P0R0. The compressive strengths of P0R0 and P1.0R0 obtained from cylindrical test samples were lower than those attained from cubic test specimens, while the compressive strengths of other cylindrical EGC mixes were either higher or comparable to those of cubic mixtures. The induced disparate compressive strengths for specimens with different sizes are due to the friction at the contact region between the specimen and the loading plate, where the lateral expansion of the test specimen is limited offering transversal compressive stress on it (Yu et al., 2020). Hence, the specimen with a large contact area with the loading plate should present a higher compressive strength. However, this statement is not valid for the results of P0R0 and P1.0R0, which can be associated with their different fracturing processes. The aspect ratio of the cylindrical sample (2.0) was larger than that of the cubic sample (1.0) here, which may have a larger mid-portion area experiencing pure tension (Wang et al., 2011b). Therefore, when the number of effective fibres within this pure tension region
reduces, the compressive strength would be much lower. This can explain why the compressive strength of cylindrical EGC samples was higher than that of cubic samples when more fibres were present. This finding is in agreement with a previous study (Zhang et al., 2022).

The incorporation of either PVA or RTP fibres did not improve the compressive strength of geopolymers but resulted in enhanced ductility. As seen in Figure 3-14b, the compressive failure of EGCs was not sudden as compared with the brittle failure of plain geopolymer mixtures. P0R0 exhibited significant damage after being subjected to a compressive load, leading to a triangular failure pattern with oblique cracks for the cubic sample or an hourglass compressive failure mode for the cylindrical specimen. By contrast, only some longitudinal cracks can be observed on the failure surface of the EGC, remaining its original shape, which can be attributed to the crack-arresting ability of fibres (Wang et al., 2020, Kan et al., 2020a, Yu et al., 2020). In general, all EGC mixtures demonstrated adequate compressive strength for basic engineering applications.

3.3.5 Elastic modulus

The elastic modulus of materials is defined as the ability to sustain the applied stress for every unit strain within the elastic region, which is strongly associated with compressive strength. Figure 3-15a illustrates the elastic modulus of geopolymers with and without fibres. As observed, P0R0 achieved the highest elastic modulus of 18.33 GPa while by comparison, the elastic modulus of all EGC mixtures was 15-36% lower, which agrees well with the tendency of quasi-static compressive strength. Previous studies (Chen et al., 2020a, Baričević et al., 2018, Khan et al., 2018b) also reported that the incorporation of synthetic fibres reduced the elastic modulus of composites as compared with plain mixtures, which can be mainly ascribed to the internal structure of the composite (e.g., porosity and fibre orientation) as well as the stiffness of incorporated fibres (Ranjbar and Zhang, 2020). Given the high stiffness of steel fibres (about 210 GPa), adding a certain amount of steel fibres (1.0-2.0%) into geopolymers can lead to a slight improvement in the elastic modulus (Khan et al., 2018b, Ganesan et al., 2013). However, as listed in Table 3-3, PVA and RTP fibres have lower elastic modulus (3.8 GPa and 41 GPa) than steel fibres and thus may partially contribute to the reduced elastic modulus of EGCs, while it was reported that fibre stiffness has a minor effect on the mechanical properties of composites before cracking (Zhang et al., 2020b). During the elastic modulus test, no visible cracking appeared on the tested
specimen. As discussed above, replacing a small dosage of PVA fibre (0.25%) with RTP fibre led to slightly better workability and quasi-static compressive strength compared to P2.0R0, implying that the specimen had a better internal structure in terms of lower porosity and better fibre distribution. Hence, the elastic modulus of P1.75R0.25 was 26% higher than that of P2.0R0. In addition, the elastic modulus of all other hybrid fibre reinforced EGC mixtures was in the range of 11.77-13.79 GPa which was either greater or comparable in comparison with P2.0R0.

Figure 3-15 Elastic modulus of EGCs: (a) effects of PVA and RTP fibre content, and (b) comparison with existing models and studies (data adapted from Refs. (Lee and Lee, 2013, Nematollahi et al., 2016, Kan et al., 2020a, Kumar et al., 2022, Khan et al., 2018b, ACI 318, 2008, CEB-FIP model code 1990: Design code, 1990)).

As mentioned previously, elastic modulus is regarded as an important index for structural designs and hence, it is vital to develop a reliable model of elastic modulus concerning compressive strength. For comparison, the proposed equations for estimating the elastic modulus of Portland cement concrete (ACI 318, 2008, CEB-FIP model code 1990: Design code, 1990) and geopolymer concrete (Lee and Lee, 2013) were plotted in Figure 3-15b, along with some data on geopolymer composites collected from previous studies (Khan et al., 2018b, Kan et al., 2020a, Nematollahi et al., 2016, Kumar et al., 2022). It can be seen that the elastic modulus of all geopolymer composites especially EGC mixtures obtained from other studies (Nematollahi et al., 2016, Kan et al., 2020a) was significantly lower than the calculated values using the equations for Portland cement and geopolymer concrete, which can be ascribed to the absence of coarse aggregates in the geopolymer composites. Increasing the silica sand content inside the EGC enhanced its elastic modulus while the elastic modulus was
still lower than the predicted elastic modulus according to the ACI 318 and CEB-FIP models (Equations (2-4) and (2-5)) (Kumar et al., 2022). These suggest that the existing models for predicting the elastic modulus would not be suitable for EGCs. However, the available elastic modulus data of EGCs is insufficient to offer a reliable model and therefore, more extensive studies are needed considering different grades of compressive strength for EGCs.

3.3.6 Splitting tensile strength

Figure 3-16a presents the quasi-static splitting tensile strength of all mixtures. The splitting tensile strength of the EGC went up with the increasing PVA fibre dosage and dropped with the increase of RTP fibre replacement level. For instance, the splitting tensile strength of P2.0R0 was 196% and 29% higher than that of the plain geopolymer mixture and the EGC with 1.0% PVA fibre, while the splitting tensile strengths of P1.75R0.25 and P1.0R1.0 were 3.4% and 18% lower as opposed to P2.0R0. When the fibre dosage within a specimen is higher, the splitting tensile strength tends to be larger as more fibres can exert the bridging effects to limit the crack development along the loading direction until fibre pull-out or fibre rupture. RTP fibres are more effective in controlling induced micro-cracks because of their shorter length, lower strength and poorer interfacial bonding with the matrix compared to PVA fibres. Hence, hybrid fibre reinforced EGCs possessed a lower load-carrying capacity than the mono-PVA fibre reinforced EGC. The synergistic effect of hybrid PVA and RTP fibres still can effectively control the crack development at different scales, which can explain the insignificant weakening effect in splitting tensile strength of EGCs induced by the presence of a certain dosage of RTP fibre (0.25-0.5%).

The splitting tensile strength can be estimated based on the compressive strength, where ACI 318 model (Equation (3-2)) and Eurocode 2 model (Equation (3-3)) have been commonly used to predict the splitting tensile strength of Portland cement concrete:

\[ f_{st} = 0.56\sqrt{f_c} \]  \hspace{1cm} (3-2)

\[ f_{st} = \frac{1}{3} (f_c)^{2/3} \]  \hspace{1cm} (3-3)

where \( f_{st} \) is the splitting tensile strength.

Besides, Lee and Lee (2013) proposed an equation to predict the splitting tensile strength of FA-GGBS based concrete based on the compressive strength:
Figure 3-16 Splitting tensile strength of EGCs: (a) Effects of PVA and RTP fibre content, and (b) comparison with existing models (ACI 318, 2008, Eurocode 2, 2004, Lee and Lee, 2013).

The splitting tensile strength results from the current study were compared with the above predictions in Figure 3-16b, indicating that the splitting tensile strength of the plain geopolymer was close to the model proposed by Lee and Lee (2013). By contrast, the splitting tensile strengths of all EGC mixes were substantially larger than all the predicted results, which can be mainly ascribed to the fibre bridging effect of EGCs.

Figure 3-17 demonstrates the typical failure patterns of the plain geopolymer and EGC, indicating that the plain geopolymer was split into two halves while the EGC specimen maintained its structural integrity accompanied by a main major crack (red solid line) and some diffuse micro-cracks (red dash line). During the splitting tensile loading, the tensile stress would mainly appear along the diameter of the tested specimen (i.e., loading direction), where the tangential stress would exceed the uniaxial tensile strength and lead to failure (Chen et al., 2014). Hence, the major crack of the failed specimen would lie within the central portion. Under the action of fibre bridging, the crack development path of the EGC was not straight (Figure 3-17b), which was different from that of the plain geopolymer (i.e., almost vertical). The appearance of diffuse micro-cracks near the major crack could be because the bridging fibres dispersed the tensile stress to surrounding areas of the major crack (Chen et al., 2020a). Based on the image of fibre conditions at the crack interface after the quasi-static splitting tension, PVA fibres were either pulled out or ruptured as the development of the major crack. The pulled out PVA fibre was more favourable for...
strength improvement. Besides, many matrix fragments adhered to the surface of the pulled out PVA fibre indicate its strong interfacial bonding with the geopolymer matrix, which can prevent the macro-crack from propagation. By contrast, the surface of the RTP fibre did not have any distinct matrix particles due to its hydrophobic surface feature. However, it still can restrain the initiated internal micro-crack and prevent it from coalescence into a macro-crack.

Figure 3-17 Typical failure pattern of (a) plain geopolymer and (b) hybrid fibre reinforced EGC.

3.3.7 Environmental impact and material cost

As stated previously, the main objective of this study is to reduce the material cost and improve the sustainability of EGCs through the partial replacement of PVA fibres. Thus, the effects of fibres on the total material cost, embodied carbon and embodied energy were analysed. Table 3-5 lists the market price, embodied carbon and embodied energy of all ingredients needed for producing EGCs in this study (Abdollahnejad et al., 2015, Rafeet et al., 2017, Zhang et al., 2020a, Ohno and Li, 2018, Hammond et al., 2008, Ranade, 2014, Fawer et al., 1999, Frazão and Fernandes, 2004, Keoleian et al., 2005). It is worth noting that the calculated material cost here was employed to reveal the potential economic benefit of using RTP fibres to substitute PVA fibres in EGCs, while the actual material cost may vary as the price of each ingredient can change with regions, manufacturers and producing years.
Table 3-5 Material cost and life cycle inventory data of each component in EGCs (data adapted from Refs. (Abdollahnejad et al., 2015, Rafeet et al., 2017, Zhang et al., 2020a, Hammond et al., 2008, Ohno and Li, 2018, Ranade, 2014, Fawer et al., 1999, Frazão and Fernandes, 2004, Keoleian et al., 2005)).

<table>
<thead>
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<th>Type</th>
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<th>Embodied carbon (kg CO(_2).eq/kg)</th>
<th>Embodied energy (MJ/kg)</th>
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</thead>
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<tr>
<td>FA</td>
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<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>GGBS</td>
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</tr>
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<td>Silica sand</td>
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<td>0.17</td>
</tr>
<tr>
<td>NaOH pellet</td>
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<td>Na(_2)SiO(_3) solution</td>
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<td>Water</td>
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<tr>
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<tr>
<td>PVA fibre</td>
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<td>101</td>
</tr>
<tr>
<td>RTP fibre</td>
<td>0.5</td>
<td>2.53</td>
<td>21.9</td>
</tr>
</tbody>
</table>

The estimated total material cost of all mixtures in USD/m\(^3\) is presented in Figure 3-18a. It can be found that the cost of PVA fibres constituted a considerably big part of the total material cost of the mono-PVA fibre reinforced EGC and it was about 70% of the total material cost. Replacing a certain content of PVA fibres (0.25-1.0%) with RTP fibres in EGCs significantly reduced the total cost by 8.6-35%. This large reduction can be attributed to the extremely lower cost of RTP fibres, which is only 1.6% that of PVA fibres. Although some other costs may be required for processing RTP fibres (Gigli et al., 2019), the huge difference in material cost between RTP fibres and PVA fibres makes the EGC containing RTP fibres promising and attractive for certain large-scale applications given the presence of adequate engineering properties.
Figure 3-18 Material cost and environmental impact of EGCs (ECC data adapted from Refs. (Wang and Li, 2007, Yang et al., 2007)).

Embodied carbon and embodied energy are considered as the major material sustainability indicators (Yu et al., 2018), which were considered to reflect the environmental impact of EGCs. Figures 3-18b and c illustrate the embodied carbon and embodied energy of all mixtures, respectively. The embodied carbon and embodied energy of two typical ECC mixes were also considered here (Wang and Li, 2007, Yang et al., 2007). As seen in Figure 3-18b, all mixtures presented a dramatically lower embodied carbon than the typical ECC mixtures as the matrix of the ECC containing a very high dosage of cement contributed significantly to the increase in embodied carbon. The embodied carbon of P2.0R0 was around 329 kg CO$_2$.eq/m$^3$, approximately 15-44% lower than that of typical ECCs. The embodied carbon gradually increased with the increase of PVA fibre dosage while no significant effect can be observed when PVA fibres were replaced with RTP fibres (purple trend line).
On the other hand, as shown in Figure 3-18c, the embodied energy of EGCs was comparable with that of ECCs. The embodied energy of the EGC presented a similar increasing trend as the PVA fibre dosage increased. By contrast, the embodied energy of the EGC reduced gradually with the rising RTP fibre replacement and the reduction was in the range of 4.1-16% compared to P2.0R0, which can be mainly ascribed to the lower embodied energy of recycled fibres, as given in Table 3-5. In addition, more solid wastes can be reduced when RTP fibres are incorporated. Overall, replacing PVA fibres with RTP fibres in EGCs can lead to an enhancement in the sustainability of construction materials considering the above results.

3.4 Summary

In this chapter, the workability, setting time, drying shrinkage, compressive strength, elastic modulus, splitting tensile strength, material cost and sustainability of EGCs with different PVA fibre dosages (1.0%, 1.5% and 2.0%) and RTP fibre replacement contents (0.25%, 0.5%, 0.75% and 1.0%) were investigated. Based on the experimental results, the main conclusions can be drawn as follows:

- The presence of either PVA or RTP fibres reduced the workability of plain geopolymers. Replacing 0.25% PVA fibre with RTP fibre did not significantly vary the workability of the EGC, while about 8-12% lower workability is observed in EGCs when more than 0.25% PVA fibre is replaced with RTP fibres in comparison with the EGC containing 2.0% PVA fibre.

- Incorporating PVA fibres into the plain geopolymer did not benefit its setting time, while the initial setting time of hybrid fibre reinforced EGCs was longer than that of mono-PVA fibre reinforced EGCs. Considering the initial setting time, all EGC mixes can fulfil the requirement for engineering application (≥ 60 min).

- Increasing the PVA fibre volume fraction up to 1.5% can effectively decrease the drying shrinkage of the EGC. As compared with the EGC incorporating 2.0% PVA fibre, the drying shrinkage of hybrid fibre reinforced EGCs was lower (e.g., up to about 17% lower at 28 d).

- Regardless of test specimen size, the incorporation of either PVA or RTP fibres did not enhance the compressive strength of plain geopolymers but remained the structural integrity of test specimens. The reduced compressive strength in the EGC due to the presence of PVA fibres can be mitigated by adding RTP fibres.
All EGC mixes attained a compressive strength of higher than 45 MPa at 28 d which is acceptable for engineering applications.

- Similar to compressive strength, no positive influence was found on the elastic modulus of plain geopolymers when either PVA or RTP fibres were added. The elastic modulus of hybrid fibre reinforced EGCs ranged from 11.77 GPa to 14.87 GPa, which was mostly larger than that of the EGC with 2.0% PVA fibre (11.84 GPa). Due to the absence of coarse aggregates and the inclusion of synthetic fibres, the commonly used equations (ACI 318 and CEB-FIP models) overestimated the elastic modulus of EGCs in this study.

- The plain geopolymer exhibited extraordinarily brittle behaviour under quasi-static splitting tension, while the presence of PVA or RTP fibres improved the splitting tensile strength of geopolymers by 129-196% and maintained the structural integrity of test samples. Increasing RTP fibre dosage in the hybrid fibre reinforced EGC led to a 3.4-18% reduction in splitting tensile strength compared to the EGC with 2.0% PVA fibre.

- The presence of RTP fibres decreased the material cost and embodied energy of the mono-PVA fibre reinforced EGC by 8.6-35% and 4.1-16%, respectively. The embodied carbon of all EGC mixes was significantly lower than that of typical ECC mixtures (e.g., the embodied carbon of the EGC with 2.0% PVA fibre was about 15-44% lower).
Chapter 4 Quasi-static tensile behaviour of EGCs

4.1 Introduction

In Chapter 3, RTP fibres were found to be feasible to incorporate into the PVA fibre reinforced EGC considering some basic engineering properties. In this chapter, the effects of different PVA fibre contents and various RTP fibre replacement dosages on the uniaxial tensile behaviour of EGCs including stress-strain response, tensile strength, tensile strain capacity, tensile strain energy and cracking pattern were investigated. Additionally, the fibre bridging behaviour, internal pore structure, fibre inclination angle and fibre distribution coefficient of mono-PVA fibre reinforced and hybrid fibre reinforced EGCs were explored to further understand the role of fibres on the uniaxial tensile behaviour of EGCs with the same mix proportions adopted in Chapter 3. Part of this chapter has been presented in the following peer-reviewed journal paper:

4.2 Test methods

4.2.1 Uniaxial tensile behaviour

The uniaxial direct tension test was carried out on the dog-bone shaped specimen at 28 d according to the recommendation of Japan Society of Civil Engineers (2008). Figure 4-1 shows the schematic and actual experimental setup and the dimension of the dog-bone shaped specimen. The dog-bone shaped specimen was loaded uniaxially with a loading rate of 0.5 mm/min and two linear variable displacement transducers (LVDTs) were installed to measure the tensile deformation at both sides of the specimen within a gauge length of 80 mm. Besides, the region of the gauge length was used for the crack analysis (Figure 4-1b). Regarding the crack analysis, the residual crack number and crack width of each tested specimen were determined using a digital microscope (WM401WIFI, Shanghai) until the load removal. Although the residual crack width could not fully represent the crack width whilst the tensile loading of the specimen, the result can still be used to evaluate the effect of fibres on the crack-controlling ability of the composite (Wu et al., 2021). Furthermore, the fibre failure status across the fracture surface was captured using a portable digital microscope.
4.2.2 Micromechanical investigation

As mentioned in Section 2.3.3, it is important to evaluate whether the studied EGC mixtures (Table 3-4) can meet the strength-based and energy-based criteria. In this study, two important indices, i.e., $\sigma_0/\sigma_{fc}$ and $J'/J_{tip}$, were experimentally determined using a series of tests. The single crack direct tension was carried out to attain the tensile stress-crack opening curve of the composite (see Figure 2-1) at 28 d and then to determine $\sigma_0$ and $\delta_0$. A schematic illustration of the experimental configuration is given in Figure 4-2. The dimension of the tested specimen here was the same as that used in the uniaxial direct tension test (see Section 4.2.1) while notches were cut around the mid-height of the specimen. The dimensions of the notched area and the remained area are given in Figure 4-2. The loading rate of the test was kept constant at 0.5 mm/min. Two LVDTs were mounted to measure the crack opening of the single crack. Through conducting the uniaxial direct tension test on the matrix mixture (P0R0) at 28 d, two parameters, $\sigma_{fc}$ and $E_m$, were subsequently evaluated. To obtain $K_m$, three-point bending test was performed on the 40 mm × 40 mm × 160 mm prismatic specimen with a notch at 28 d under a constant loading rate of 1 mm/min according to RILEM FMC-50 (1985), the experimental configuration of which is presented in Figure 4-3. The thickness, length and depth of the single notch were 1
mm, 40 mm and 12 mm, respectively. $K_m$ can be calculated by (Xu and Reinhardt, 1999):

$$K_m = \frac{1.5 \left( F_p + \frac{m_s g}{2} \times 10^{-2} \right) \times 10^{-3} \times S \times a_0^2}{t_s h_s^2} f(a)$$

$$f(a) = \frac{1.99 - a (1 - a) (2.15 - 3.99a + 2.7a^2)}{(1 + 2a)(1 - a)^{3/2}}$$  \(4-1\)

$$a = \frac{a_0}{h}$$

where $F_p$ is the peak load recorded during the three-point bending test, $m_s$ is the mass of the tested specimen, $S$ is the loading span, $a_0$ is the depth of the notch, $t_s$ is the thickness of the tested specimen, and $h_s$ is the height of the tested specimen.

![Figure 4-2 Notched dog-bone shaped specimen for single crack tension test.](image)

![Figure 4-3 Schematic diagram of the experimental setup for three-point bending test.](image)
4.2.3 Microstructure characterisation

Several pieces of samples were obtained from the fracture surface of the specimen after the uniaxial tensile test and then characterised using SEM equipment (FEI, QUANTA FEG 250, USA). The objective was to explore the surface condition and failure mode of the fibres across the fracture surface, which are important to the understanding of the fracture mechanism of EGCs. Regarding the SEM test, the acceleration voltage was set as 20 kV while the working distance was around 10 mm.

As discussed in Chapter 2, the macroscopic properties of EGCs especially uniaxial tensile behaviour are strongly associated with its internal pore structure. Therefore, XCT test was performed to characterise the pore structure of mono-PVA fibre reinforced and hybrid fibre reinforced EGCs to gain insight into their relation with mechanical properties. A small block was cut from the middle section of the dog-bone shaped EGC specimen for XCT imaging with a resolution of about 6.8 μm/voxel. The XCT data was processed using VG Studio to reconstruct the 3D pore structure and evaluate pore size distribution. The global thresholding method based on the grey value of images was employed to segment different phases in EGCs (Zeng et al., 2019).

Except for the pore structure, the distribution and orientation of fibres in EGCs are also essential for the mechanical properties of EGCs. Therefore, the analysis of BSE images on the mono-PVA and hybrid fibre reinforced EGC mixes were carried out. It was reported that under BSE imaging, fibres and the matrix can be clearly identified because of their different component characteristics (atomic numbers) (Ding et al., 2020a, Lei et al., 2019). The test samples were cut from the middle section of the dog-bone shaped EGC samples. Before BSE imaging, the sample surface should be well polished for obtaining a smooth and flat surface. Firstly, the samples were impregnated by an epoxy solution, which can fill the pores of the specimens before polishing. This stage can help stabilise the microstructure of the test sample and it can better withstand the stress of polishing (Kjellsen et al., 2003). Then, the automatic pressure polishing machine was used to polish the test sample. To capture the fibre distribution, the polished sample was divided into 20 units, where each unit had a size of about 2 mm × 1.4 mm. The adopted number of units in this study was similar to those utilised in existing studies on ECCs (Zhu et al., 2022, Ding et al., 2020b). In terms of the fibre orientation, typically three patterns including circle, ellipse and strip can be formed for the cross-section of fibres on the cut surface, as indicated in Figure 4-4. Herein, the fibre inclination angle of these fibres (θ) is defined as the angle between the fibre axis
and the normal direction of the fracture surface (see Figure 4-4) and can be derived using the following equation:

\[ \theta = \arccos \frac{d_f}{L_f} \]  

(4-2)

Additionally, the fibre distribution coefficient \( \alpha_f \) representing the number of fibres per unit area was used to quantitatively investigate the fibre distribution degree in EGCs (Equation (4-3)). Several studies have utilised this parameter to study the fibre dispersion degree of ECCs (Zhu et al., 2022, Li and Li, 2013, Ding et al., 2020a) and other fibre reinforced cementitious composites (Xie et al., 2020). A more uniform fibre distribution is in the selected area when the fibre distribution coefficient is closer to 1.

\[ \alpha_f = \exp \left( -\frac{1}{\bar{x}} \sqrt{\frac{\sum(x_i - \bar{x})^2}{n}} \right) \]  

(4-3)

where \( \bar{x} \) is the average number of fibres in all images, \( x_i \) represents the number of fibres in the \( i \)-th image, and \( n \) stands for the total number of adopted images (20 in this study).

Figure 4-4 Schematic diagram of fibre inclination angle (Zhu et al., 2022, Ding et al., 2020b).
4.3 Results and discussion

4.3.1 Tensile stress-strain response

Figure 4-5 depicts the tensile stress-strain curves of all mixtures. It should be noted that only two curves were present for P1.5R0.5 as the tensile failure of the third specimen did not occur within its gauge region. Similar to the tensile stress-strain response discussed in Section 2.4.5.1, the tensile stress-strain curves of all mixes here contained two distinct regions, an elastic region and a strain-hardening or strain-softening region. During the elastic region, the tensile stress of the tested sample increased rapidly and linearly with a small change of strain before reaching the elastic limit that was regarded as the transition point between the linearity region and non-linearity region, also known as first cracking strength. After that, the tested sample either experienced steady rising stress (strain-hardening) or gradual decreasing stress (strain-softening) with the increase of strain. The highest point of stress was tensile strength and the corresponding strain was tensile strain capacity. As seen in Figure 4-5, P0R0 had a very brittle tensile behaviour and failed immediately after reaching its tensile limit. Remarkably, P1.5R0, P2.0R0, P1.75R0.25 and P1.5R0.5 displayed an apparent strain-hardening phenomenon while the strain-hardening behaviour of P1.0R0 and P1.25R0.75 was not pronounced. P1.0R1.0 even lost the strain-hardening feature but exhibited strain-softening behaviour after exceeding the first cracking strength. Regarding the effects of PVA (Figure 4-5a) and RTP fibres (Figure 4-5b), it can be found that with the increase of PVA fibre dosage, the strain-hardening region was consistently prolonged whereas the strain-hardening behaviour was weakened when more RTP fibres replaced PVA fibres. The uniaxial tensile properties including first cracking strength, tensile strength, tensile strain capacity and tensile strain energy derived from the stress-strain curves are discussed below to further estimate the effect of fibres on the uniaxial tensile behaviour of EGCs.

It should be noted that multiple regimes of behaviour can be evident from Figure 4-5. All EGCs initially showed a linear elastic behaviour, but then they diverged to present either a steep drop (e.g. P1.0R0) or strain-hardening behaviour (e.g. P1.5R0) followed eventually by some ductility seen as levelling out of the stress-strain curve towards failure (e.g. P1.75R0.25). The strain-hardening behaviour after the elastic limit can be caused possibly by an increasing fibre-to-matrix bond stress as the fibres were progressively pulled out from the matrix, while the ductility was likely attributed
to a constant fibre-to-matrix bond stress as the fibres experienced sliding pull-out from the matrix.

Figure 4-5 Tensile stress-strain response: (a) effect of PVA fibre content and (b) effect of RTP fibre content.

4.3.2 Tensile properties

Figure 4-6 summarises the typical tensile properties of EGCs. The first cracking strength of EGCs is mainly dependent on its matrix (e.g., $K_m$) and no clear trend of change in the first cracking strength of the EGC can be found when the fibre dosage altered. All EGC mixtures had a first cracking strength ranging from 1.28 MPa to 2.42 MPa, which mostly was higher than the first cracking strength of P0R0 due to the fibre bridging effect inside the composite (Yang and Li, 2007). P2.0R0 had the highest first cracking strength of 2.42 MPa, which is consistent with the finding of Ohno and Li (2018) that the first cracking strength of the PVA fibre reinforced EGC was increased by 1.0 MPa when the PVA fibre volume fraction changed from 1.0% to 2.0%. As compared with P2.0R0, the first cracking strength of EGCs containing RTP fibres was lower, especially when the RTP fibre content was higher than 0.5%. Since all studied EGC mixes here shared the same matrix, $K_m$ was not the dominant factor influencing the first cracking strength. As discussed in Section 2.4.5.2, in addition to $K_m$, the first cracking strength of EGCs can be also affected by its internal pore structure and the fibre bridging behaviour if the internal pore is bridged by the fibres (Li, 2019). When more PVA fibres were present, the first cracking strength of the whole composite tended to be higher, which can be ascribed to the effective fibre bridging action of PVA fibres (Yang and Li, 2007, Ohno and Li, 2018). This can be evidenced that the
first cracking strength of P1.0R1.0 was 24% lower than that of P1.0R0. Similar findings were captured by other studies (Choi et al., 2022, Ohno and Li, 2018).

Figure 4-6 Effects of PVA and RTP fibre content on (a) first cracking strength, (b) tensile strength, (c) tensile strength capacity, and (d) tensile strain energy of EGCs.

Converse to compressive strength, the increase of PVA fibre dosage led to an increase in tensile strength of the EGC by 57-124% as compared with P0R0 (Figure 4-6b). It is worth noting that the tensile strength of P2.0R0 (3.4 MPa) in this study was comparable to that of the FA-GGBS based EGC with an activator modulus of 1.5 (Zhang et al., 2020c). The significant enhancement in tensile strength due to the increase of PVA fibre dosage can be associated with the fibre distribution and orientation as well as the fibre bridging action. It can be suggested that when more PVA fibres are present, the number of efficient bridging fibres tends to increase, in turn, significantly improving the tensile strength of EGCs. It should be noted that fibres are regarded as 2D randomly distributed inside the dog-bone shaped specimen and can
have different embedment lengths and inclination angles (Yu et al., 2018), affecting the tensile performance of the whole composite. These will be discussed further in Section 4.3.5. By contrast, adding RTP fibres into the EGC decreased the tensile strength. More specifically, the tensile strength of P1.0R1.0 was only 1.68 MPa which was 30% lower than that of P1.0R0. However, the negative influence of 0.5% RTP fibre on the tensile strength of the EGC was limited, only 3.8% lower as compared with P1.5R0. The loss in tensile strength due to the addition of recycled fibres is in consistence with previous studies on ECCs (Choi et al., 2012, Yu et al., 2018). Following the same trend of first cracking strength, a lower tensile strength of the EGC can be found when it contained more RTP fibres, which can be mainly ascribed to the lower bridging stress of RTP fibres in comparison with PVA fibres. If the cracking plane has more RTP fibres instead of PVA fibres, the localisation of fracture would happen, and no more new cracks can be induced because of the insufficient bridging stress to restrain the crack opening. However, all EGC specimens containing hybrid PVA and RTP fibres showed higher tensile strength than P0R0.

Figure 4-6c shows the tensile strain capacity of all mixtures. It can be observed that the influence of fibres on the tensile strain capacity was similar to that on the tensile strength. For instance, the tensile strain capacity of the EGC was increased with the increasing PVA fibre dosage, where the values of P1.0R0, P1.5R0 and P2.0R0 were about 16-255 times larger than that of P0R0 (only 0.01%). P2.0R0 had a tensile strain capacity of 3.04% which was higher than that of M45 ECC (2.49%), reported by Ref. (Wang and Li, 2007). Although EGCs containing RTP fibres showed a lower tensile strain capacity than P2.0R0, they still outperformed P0R0 by 2-188 times. On the other hand, as mentioned in Section 2.4.5.3, the tensile strain energy can be also used to reflect the strain-hardening degree of EGCs, which is defined as the energy dissipation capacity per unit volume during the strain-hardening region and can be calculated by integrating the ascending branch of the tensile stress-strain curve. The calculated strain energy of all mixtures is presented in Figure 4-6d, which agrees well with the results of tensile strength and tensile strain capacity. P2.0R0 had the highest strain energy of about 90 kJ/m³, representing the best strain-hardening performance.

4.3.3 Cracking analysis

The typical tensile fracture patterns of all mixtures are illustrated in Figure 4-7. It should be noted that the image of P0R0 was taken after tensile failure while the images of EGC specimens were captured before unloading. The cracking patterns here are
consistent with the stress-strain curves shown in Figure 4-5 that obvious multiple cracking features can be observed for P1.5R0, P2.0R0, P1.75R0.25 and P1.5R0.5 (Figures 4-7c-f) along with clear strain-hardening features. Only several cracks can be observed for P1.0R0, P1.25R0.75 and P1.0R1.0. Independent of fibre type and fibre dosage, the presence of fibres improved the post-cracking behaviour of EGCs compared to the brittle failure of P0R0 (Figure 4-7a). In addition, more uniformly distributed cracks can be found in P2.0R0, which are consistent with its best tensile properties, as discussed previously.

Figure 4-7 Representative tensile cracking patterns of all mixtures: (a) P0R0, (b) P1.0R0, (c) P1.5R0, (d) P2.0R0, (e) P1.75R0.25, (f) P1.5R0.5, (g) P1.25R0.75, and (h) P1.0R1.0.

Table 4-1 lists the residual crack number and crack width of EGCs after the removal of tensile load. The actual crack widths should be smaller than the residual
crack widths as many micro-cracks are closed upon the removal of tensile load (Li et al., 2001). There exists a similar trend of residual crack number with that of tensile strain capacity. A large standard deviation can be noticed for P1.5R0, mainly due to the random fibre distribution between each sample even from the same batch of mixing (Zhang et al., 2020c). The performance of P2.0R0 was more stable as the coefficient of variation (COV) of the residual crack number was only 3.6%. On the other hand, the residual crack width of the EGC was smaller when more PVA fibres were present, where the crack-controlling behaviour was affected by the fibre-matrix interface. As seen in Figure 4-8a, at the fracture surface of the EGC, most PVA fibres were pulled out, implying that the bond strength between fibres and matrix is adequate to avoid fibre rupture. Such fibre-matrix interface behaviour is favourable for improving the tensile behaviour and restraining the crack width, given that the bridging fibre has high enough tensile strength (Zhao et al., 2021b). However, some PVA fibres were ruptured, which can be associated with their interfacial behaviour with the matrix, inclination angles and embedment lengths. Although RTP fibres also experienced pull-out behaviour during the tensile loading (Figure 4-8b), the short length and low tensile strength limited the crack-controlling behaviour of the whole composite. Thus, a larger crack width was found in the EGC when more RTP fibres were added. This regard will be further discussed in Sections 4.3.4 and 4.3.5 through the analysis of micromechanical and microstructural investigation.

Table 4-1 Residual crack number and crack width after uniaxial tension test.

<table>
<thead>
<tr>
<th>Mixture label</th>
<th>Average crack number</th>
<th>Average crack width (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1.0R0</td>
<td>4 (1)</td>
<td>218.9 (62.6)</td>
</tr>
<tr>
<td>P1.5R0</td>
<td>27 (15)</td>
<td>34.3 (7.5)</td>
</tr>
<tr>
<td>P2.0R0</td>
<td>28 (1)</td>
<td>29.8 (11.6)</td>
</tr>
<tr>
<td>P1.75R0.25</td>
<td>26 (2)</td>
<td>33.5 (2.2)</td>
</tr>
<tr>
<td>P1.5R0.5</td>
<td>17 (2)</td>
<td>39.2 (0.2)</td>
</tr>
<tr>
<td>P1.25R0.75</td>
<td>8 (6)</td>
<td>124.7 (75.4)</td>
</tr>
<tr>
<td>P1.0R1.0</td>
<td>3 (1)</td>
<td>379.9 (190.0)</td>
</tr>
</tbody>
</table>

Note: the values in parentheses are standard deviations.

In summary, the average residual crack widths of P1.5R0, P2.0R0, P1.75R0.25 and P1.5R0.5 were in the range of 29.8-39.2 μm, similar to those reported in a typical ECC (60 μm) (Li et al., 2001) and other EGCs (24.0-84.2 μm) (Zhang et al., 2020c, Zhao et al., 2021b). These tight crack widths indicate a strong crack-controlling ability of
EGCs and are beneficial for many engineering properties, e.g., durability and self-healing performance (Qiu et al., 2016).

Figure 4-8 Fibre conditions across the tensile fracture surfaces of EGCs: (a) mono-PVA fibre reinforced EGC and (b) hybrid fibre reinforced EGC.

4.3.4 Micromechanical investigation

4.3.4.1 Stress-crack opening response

Figure 4-9 illustrates the representative tensile stress-crack opening curves of EGCs from the single crack direct tension tests. The experimental results of $\sigma_0$ and $\delta_0$ are summarised in Table 4-2. The shape of the curves shown in Figure 4-9 is affected by the dosage and properties of fibre and more importantly, the interface properties between fibre and matrix (Li, 2019). $\sigma_0$ is largely affected by $G_d$ and $\tau_0$ (Li, 2019, Zhang et al., 2020c). Thus, the increasing branch of the curve shown in Figure 4-9 represents the required stress to overcome the bond and pull out the bridging fibres. After exceeding it, the fibres can no longer bridge the crack and are either pulled out completely or ruptured. With the increase of PVA fibre dosage, $\sigma_0$ of the EGC was consistently increased, which explains why P2.0R0 presented the best tensile performance as shown in previous sections. By contrast, increasing the RTP fibre replacement dosage led to a lower $\sigma_0$ for the EGC ranging from 1.08-2.02 MPa, which indicates that the tensile behaviour was diminished. Regarding $\delta_0$, similar to $\sigma_0$, P2.0R0 had the highest value of 0.308 mm while there exhibited a general decreasing trend in $\delta_0$ as the PVA fibre dosage in the EGC reduced. It was found that a higher $\delta_0$ would benefit the tensile strain capacity as higher stress is required to pull the bridging fibres out (Yu et al., 2019).
Figure 4-9 Representative tensile stress-crack opening response of all mixtures.

Table 4-2 Results of single crack tension test.

<table>
<thead>
<tr>
<th>Mixture label</th>
<th>Fibre bridging stress, $\sigma_0$ (MPa)</th>
<th>Corresponding crack opening, $\delta_0$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1.0R0</td>
<td>1.20 (0.157)</td>
<td>0.114 (0.014)</td>
</tr>
<tr>
<td>P1.5R0</td>
<td>1.91 (0.126)</td>
<td>0.157 (0.048)</td>
</tr>
<tr>
<td>P2.0R0</td>
<td>2.56 (0.130)</td>
<td>0.308 (0.030)</td>
</tr>
<tr>
<td>P1.75R0.25</td>
<td>2.02 (0.172)</td>
<td>0.218 (0.030)</td>
</tr>
<tr>
<td>P1.5R0.5</td>
<td>1.64 (0.161)</td>
<td>0.112 (0.036)</td>
</tr>
<tr>
<td>P1.25R0.75</td>
<td>1.51 (0.155)</td>
<td>0.083 (0.032)</td>
</tr>
<tr>
<td>P1.0R1.0</td>
<td>1.08 (0.140)</td>
<td>0.140 (0.048)</td>
</tr>
</tbody>
</table>

Note: the values in parentheses are standard deviations.

4.3.4.2 Strain-hardening indices

To further interpret the results of tensile behaviour and verify whether the proposed mixtures here achieve a saturated strain-hardening phenomenon, two strain-hardening indices related to strength-based and energy-based criteria were determined. As mentioned in Section 2.3.3, two following conditions need to be satisfied to achieve a saturated strain-hardening behaviour: (1) $\sigma_0/\sigma_{fc} \geq 1.2$; (2) $J'/J_{tip} \geq 2.7$. The results of fracture toughness for P0R0 are shown in Table 4-3, which were used to determine $J_{tip}$. Table 4-4 lists the strain-hardening indices of all EGC mixtures. It can be found that P1.5R0, P2.0R0 and P1.75R0.25 satisfied the above two conditions, which are consistent with the stress-strain curves and cracking patterns shown in Figure 4-5 and Figure 4-7, respectively. P2.0R0 achieved the highest values in both indices, implying that it had a higher tendency to achieve a robust strain-hardening feature along with a
stable multiple cracking behaviour (Kanda and Li, 2006). However, as observed from Table 4-4, P1.5R0.5 did not satisfy the requirements for a saturated strain-hardening behaviour although its stress-strain curve showed an obvious strain-hardening region. This phenomenon was also reported by Nematollahi et al. (2017e) that pronounced strain-hardening and multiple cracking features were observed but $PSH_{\text{energy}}$ was only around 2.0. It is interesting to note that $PSH_{\text{strength}}$ here was positively correlated to the tensile strain capacity shown in Figure 4-6c, where a higher $PSH_{\text{strength}}$ corresponded to a higher tensile strain capacity, while $PSH_{\text{energy}}$ showed a slight inconsistency. For instance, the tensile strain capacity of P1.5R0.5 was considerably larger than that of P1.0R0 (0.96% versus 0.01%) but P1.0R0 possessed a higher $PSH_{\text{energy}}$ than P1.5R0.5. This can be attributed to the deviations of the results, which are also reported in a previous study (Zhao et al., 2021b). It is worth noting that the deviations tended to be higher when more RTP fibres were incorporated into the EGC, indicating the important role of PVA fibres in tensile performance. Additionally, this suggests that the tensile behaviour of hybrid fibre reinforced EGCs may be less sensitive to $PSH_{\text{energy}}$.

Table 4-3 Fracture toughness of plain geopolymer (P0R0).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Mass, $m_s$ (kg)</th>
<th>Peak load, $F_p$ (kN)</th>
<th>Fracture toughness, $K_m$ (MPa·m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.489</td>
<td>1.12</td>
<td>0.572</td>
</tr>
<tr>
<td>2</td>
<td>0.481</td>
<td>1.23</td>
<td>0.628</td>
</tr>
<tr>
<td>3</td>
<td>0.492</td>
<td>1.10</td>
<td>0.562</td>
</tr>
<tr>
<td>4</td>
<td>0.482</td>
<td>0.94</td>
<td>0.480</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.560 (0.061)</td>
</tr>
</tbody>
</table>

Note: the values in parentheses are standard deviations.
Table 4-4 Calculated strain-hardening indices of EGCs.

<table>
<thead>
<tr>
<th>Mixture label</th>
<th>Strength criterion, $PSH_{strength}$</th>
<th>Energy criterion, $PSH_{energy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{fc}$ (MPa)</td>
<td>$\sigma_0/\sigma_{fc}$</td>
</tr>
<tr>
<td>P1.0R0</td>
<td>0.79 (0.104)</td>
<td></td>
</tr>
<tr>
<td>P1.5R0</td>
<td>1.26 (0.083)</td>
<td></td>
</tr>
<tr>
<td>P2.0R0</td>
<td>1.69 (0.086)</td>
<td></td>
</tr>
<tr>
<td>P1.75R0.25</td>
<td>1.52</td>
<td>1.33 (0.114)</td>
</tr>
<tr>
<td>P1.5R0.5</td>
<td>1.08 (0.106)</td>
<td></td>
</tr>
<tr>
<td>P1.25R0.75</td>
<td>1.00 (0.102)</td>
<td></td>
</tr>
<tr>
<td>P1.0R1.0</td>
<td>0.71 (0.092)</td>
<td></td>
</tr>
</tbody>
</table>

Note: the values in parentheses are standard deviations.

4.3.5 Microstructure characterisation

In this section, only the microstructures of P2.0R0 and P1.75R0.25 were characterised as in comparison with other hybrid fibre reinforced EGC mixes, P1.75R0.25 presented the best uniaxial tensile behaviour that was comparable to P2.0R0. Figure 4-10 shows the SEM images of fibre morphology in the mono-PVA fibre reinforced EGC at the tensile fracture surfaces. Most of the PVA fibres experienced pull-out behaviour (Figure 4-10a) which is in consistence with Figure 4-8a. However, the ruptured PVA fibre with a necking end and several scratches can also be observed in Figure 4-10b. Under adequate frictional stress, PVA fibres tended to be pulled out, where typically matrix fragments were attached to the fibre (Figure 4-10c). The sufficient frictional stress can be also seen in Figure 4-10d that no obvious gap was found between the fibre and matrix (red dash circles). Overall, not only the number of effective bridging fibres increases when the PVA fibre dosage increases but also the number of pull-out fibres increases. These ultimately result in higher tensile strength and larger tensile strain capacity for the EGC. On the other hand, Figure 4-11 displays the SEM images of fibre morphology in the hybrid fibre reinforced EGC. The pull-out RTP fibre can be identified which coincides with that shown in Figure 4-8b. As explained previously, RTP fibres have a weaker bond with the matrix because of the hydrophobic feature, which can be supported by Figure 4-11b that a clear void space was observed between the RTP fibre and the matrix. Besides, no pronounced matrix fragments were attached to the RTP fibre. Therefore, the pull-out process can be easily facilitated and terminated quickly. This explains why more RTP fibres in the EGC would result in lower tensile properties and a larger crack width. However, when the
incorporated RTP fibre content is appropriate, PVA and RTP fibres can form a synergistic effect to improve the crack-controlling behaviour of the whole composite.

Figure 4-10 SEM images of fibre morphology in mono-PVA fibre reinforced EGC after uniaxial tensile failure.

Figure 4-11 SEM images of fibre morphology in hybrid fibre reinforced EGC after uniaxial tensile failure.

Figure 4-12 presents the 3D pore structures of P2.0R0 and P1.75R0.25 and their pore size distribution. It should be noted that only the pores with a diameter of larger than 0.2 mm were considered here due to the limited resolution (Lu et al., 2018a, Xu et al., 2022). As seen in Figures 4-12a and b, more than 99% of the pores in P2.0R0 and P1.75R0.25 had a size less than 0.1 mm$^3$ and reducing the PVA fibre content in the EGC resulted in more fine pores. As seen in Figure 4-12c, although the percentages of pores with a diameter of 0.2-0.4 mm by the total number of pores for both mixtures
were similar, the total volume of these pores for P1.75R0.25 (4.66 mm$^3$) was larger than that of P2.0R0 (4.01 mm$^3$). This can be attributed to the smaller aspect ratio of RTP fibres compared to PVA fibres, which would introduce more air bubbles with smaller sizes whilst mixing. When the pore diameter was within 0.45–0.85 mm, the percentage of pores by the total number of pores and total volume for P2.0R0 (4.84% and 2.24 mm$^3$) were higher than those of P1.75R0.25 (3.40% and 1.80 mm$^3$), implying a larger probability of active flaw, which is defined as the flaw that can initiate the new crack when the tensile stress is lower than the bridging capacity of fibres (Xu et al., 2022). In addition, the size of the largest pore in P2.0R0 was bigger than that in P1.75R0.25. It was reported that the cracking is easier to be induced by the largest pore instead of a group of smaller pores (Lu et al., 2018a). These can explain why the multiple cracking behaviour of P2.0R0 was more significant than that of P1.75R0.25. It is worth mentioning that the cracking behaviour of composites is not affected by the size of the pore but also its shape (Lu et al., 2018a). The total porosity by volume of the scanned block of P2.0R0 and P1.75R0.25 was 3.64% and 3.04%, respectively, which can support the previous discussion that the presence of PVA fibres can induce higher porosity for the EGC, weakening the drying shrinkage resistance and elastic modulus. This was also reported in Refs. (Liu et al., 2021, Long et al., 2021) that the addition of PVA fibres can entrap more air bubbles during the mixing process.

On the other hand, the fibre bridging behaviour plays a dominant role when the crack appears during the uniaxial tension loading, which can be affected by fibre distribution and orientation. Figure 4-13 presents the examples of XCT images for P2.0R0 and P1.75R0.25, revealing that fibres in both mixtures tended to be randomly distributed and orientated. The fibres distributed parallel to the loading direction are more effective in bridging the cracks and improving the ductility of composites. The fibre distribution and orientation of P2.0R0 and P1.75R0.25 will be further discussed using the results of BSE analysis.
Figure 4-12 3D pore structure of (a) P2.0R0 and (b) P1.75R0.25, and (c) pore size distribution of them obtained from XCT imaging.
Figure 4-13 Fibre distribution in EGCs obtained from XCT: (a) P2.0R0 and (b) P1.75R0.25.

Figure 4-14 depicts some examples of BSE images for P2.0R0 and P1.75R0.25, where the epoxy impregnated pores, fibres, and silica sand were presented in black, dark grey and light grey, respectively. Similar to Figure 4-13, the fibres in P2.0R0 and P1.75R0.25 were also randomly distributed. As discussed in Section 2.4.5.2, the fibre failure mode after uniaxial tensile loading can be strongly influenced by the fibre inclination angle. The fibre inclination angle distributions of P2.0R0 and P1.75R0.25 are presented in Figure 4-15, indicating that most fibre inclination angles of both mixes were within the ranges of 10–40°. For instance, about 86% of fibres in P2.0R0 had an inclination angle of 10–40°, while around 81% of fibres in P1.75R0.25 were inclined at 10–40°. For the fibre inclination angle ranging from 0° to 20°, P1.75R0.25 had a higher proportion than P2.0R0, while P2.0R0 possessed a higher proportion when the fibre inclination angle range was 20° to 40°. The average fibre inclination angles of P2.0R0 and P1.75R0.25 were 28.5° and 27.9°, respectively, suggesting that most fibres in both mixtures can better exhibit the fibre bridging action at the cracking interfaces. As mentioned in Section 2.4.5.2, fibres with lower inclination angles can enhance the efficiency of fibre bridging action since the fibre strength would be considerably impaired when the fibre has a larger inclination angle, weakening the uniaxial tensile behaviour (Li et al., 2021b, Li, 2019).

Regarding the fibre distribution coefficient, P1.75R0.25 had a value of 0.802 which was larger than that of P2.0R0 (0.724). This can support the previous discussion that
replacing 0.25% PVA fibre with RTP fibre can lead to better fibre distribution for the EGC. In addition to the fibre inclination angle and fibre distribution coefficient, the centroidal distance of the inclined fibres can also influence the overall fibre bridging capacity of the composites (Li, 2019). As seen in Figure 4-16, fibre 5 can still offer the bridging effect while fibre 4 is not counted as the bridging fibre at the cracking plane owing to its large centroidal distance ($\geq \left(\frac{L_f}{2}\right) \cos(\theta)$).

Figure 4-14 BSE images of (a) P2.0R0 and (b) P1.75R0.25 with different distribution and orientation.

Figure 4-15 Fibre inclination angle distribution of P2.0R0 and P1.75R0.25.
4.3.6 Optimal mixtures

To comprehensively evaluate the feasibility of RTP fibres in EGCs, the overall performance between the mono-fibre reinforced EGC (P2.0R0) and hybrid fibre reinforced EGCs was compared. A comparison in terms of key engineering properties, total material cost and environmental impact is presented in Figure 4-17, where all values of P2.0R0 were set as 1.0 while the results of hybrid PVA-RTP fibre reinforced EGCs were regulated based on those of P2.0R0. It can be found that apart from the improved sustainability and the reduced material cost, the dosage of RTP fibres in the EGC should be limited to ensure its applicability, resilience, and long-term durability. Overall, the addition of RTP fibres in the EGC is beneficial for compressive strength and especially drying shrinkage resistance whereas the tensile behaviour is significantly diminished. P1.75R0.25 can be regarded as the most cost-effective mixture as it processed adequate engineering properties, lower cost and better sustainability as compared with P2.0R0. In addition, P1.5R0.5 with a tensile strain capacity of around 1.0% and the improved shrinkage-resistance is also promising for certain applications, where better controlling of early-age cracking is required, e.g., repair of existing concrete structures.
Figure 4-17 Properties, material cost and environmental impact comparison between mono-PVA fibre reinforced and hybrid fibre reinforced EGCs.

4.4 Summary

In this chapter, the uniaxial tensile behaviour including stress-strain response, tensile strength, tensile strain capacity, tensile strain energy and cracking pattern of EGCs with different dosages of PVA (1.0%, 1.5% and 2.0%) and RTP fibres (0.25%, 0.5%, 0.75% and 1.0%) was investigated. In addition, the fibre bridging behaviour and microstructure of EGCs were explored to further interpret the effects of PVA and RTP fibres on the uniaxial tensile behaviour of EGCs. Based on the experimental results, the main conclusions can be drawn as follows:

- The tensile properties of EGCs including tensile strength, tensile strain capacity and tensile strain energy were considerably improved with the increase of PVA fibre dosage while these properties were reduced when more PVA fibres were replaced with RTP fibres. The EGC with 2.0% PVA fibre presented the best tensile properties among all studied mixes, where its tensile strength, tensile strain capacity and tensile strain energy were 3.4 MPa, 3.04% and 89.94 kJm⁻³, respectively. EGC mixes containing more PVA fibres possessed more cracks under uniaxial tensile loading with tighter crack widths.

- EGC mixtures with mono PVA fibre (1.5% and 2.0%) and hybrid fibres (1.75% PVA and 0.25% RTP) presented robust tensile strain-hardening and saturated multiple cracking features according to the results of stress-strain response, fracture pattern and strain hardening indices.
• SEM micrographs indicated more pulled out PVA fibres appeared at the tensile fracture surface of the EGC, which was favourable for the improvement of tensile properties, while a weaker bond was observed at the interface between the RTP fibre and the matrix, resulting in poor tensile behaviour of EGCs.

• The utilisation of PVA fibres can induce higher porosity for the EGC compared to RTP fibres. The fibre inclination angles of the EGC with 2.0% PVA fibre were comparable to those of the mix containing 1.75% PVA fibre and 0.25% RTP fibre in the picked area. Moreover, the latter mix had a better fibre distribution considering the fibre distribution coefficient, which can benefit some basic engineering properties such as compressive strength.

• A comparison of the overall composite performance between mono-PVA fibre reinforced and hybrid PVA-RTP fibre reinforced EGCs indicated that the most cost-effective combination for the EGC is 1.75% PVA fibre and 0.25% RTP fibre, as it exhibited adequate engineering properties, lower material cost and better sustainability in comparison with the EGC with 2.0% PVA fibre.
Chapter 5 Dynamic compressive behaviour of EGCs

5.1 Introduction

Except for fresh properties and quasi-static mechanical properties, understanding the dynamic mechanical properties of EGCs is essential to promote their widespread application, especially under extreme loading conditions. This chapter presents a systematic experimental study on the effects of PVA fibre volume fraction (1.0%, 1.5% and 2.0%) and RTP fibre volume fraction (0.25%, 0.5%, 0.75% and 1.0%) on the dynamic compressive behaviour of EGCs under various strain rates (54.43-164.13 s⁻¹). In particular, the dynamic stress-strain response, failure pattern, dynamic compressive strength, DIF and energy absorption capacity were analysed and discussed. Besides, microstructural images at the fracture surfaces were used to explore the underlying mechanisms of the fibre bridging effects under dynamic compression. Part of this chapter has been presented in the following peer-reviewed journal paper:


5.2 Test methods

It should be noted that the raw materials and mix proportions used in this chapter were the same as those adopted in Chapter 3 (see Sections 3.2.1 and 3.2.2). The dynamic compressive behaviour of all mixtures was evaluated using a SHPB with a diameter of 100 mm. Figure 5-1 presents the schematic illustration and picture of the SHPB testing system, the main components of which include a striker bar (600 mm), an incident bar (5000 mm), a transmission bar (3500 mm) and an absorbing bar (1200 mm) that are all made of high-strength steel materials. The velocity of the striker bar can be adjusted by either varying the pressure level or changing the depth of the striker bar inside the launch tube. In this study, the depth of the striker bar was fixed while the pressure level was altered from 0.4 MPa to 1.0 MPa to generate various impact velocities. Three specimens were used for each pressure level. Before the test, the test specimen was first sandwiched between the incident bar and the transmission bar. The used specimen had a diameter of 100 mm and a length of 50 mm (aspect ratio: 0.5), which was selected to eliminate the axial inertia effect during the impact loading (Bertholf and Karnes, 1975, Khan et al., 2018a). In addition, the end surfaces of the
specimen were applied with a small amount of grease to minimise the end friction effect. It should be noted that 12 test specimens were prepared for each mixture and their end surfaces were all treated to ensure flatness. Once the test was started, the striker bar was launched by the immediate release of the compressed nitrogen in the pressure vessel and then it accelerated inside the launch tube until impacting the incident bar, generating an incident wave. When the incident wave reached the interface between the incident bar and the specimen, part of the wave was reflected, and the rest propagated along the transmission bar. The incident pulse ($\varepsilon_i(t)$), reflected pulse ($\varepsilon_r(t)$) and transmission pulse ($\varepsilon_t(t)$) were recorded by the strain gauges.

![SHPB apparatus: (a) schematic illustration and (b) picture of the actual device.](image)

In this study, the pulse shaping technique was used to ensure the validity of SHPB test results by filtering out the high-frequency components in the incident pulse and achieving the dynamic stress equilibrium (Chen and Song, 2011, Yu et al., 2021). As illustrated in Figure 5-1a, a small piece of rubber was placed on the impact end of the incident bar, which changed the shape of the incident pulse to extend its rising time for better facilitating the dynamic stress equilibrium (Gama et al., 2004, Chen and Song, 2011). It should be noted that the rising time of the incident pulse can be increased by either reducing the diameter of the pulse shaper or raising its thickness (Bagher Shemirani et al., 2016). Thus, trial tests were performed to select the suitable dimension of the pulse shaper. The rubber with a diameter of 30 mm and a thickness
of 3 mm was found to be adequate for producing dynamic stress equilibrium, which was similar to those employed by other studies (Khan et al., 2018a, Huang and Xiao, 2020). Figure 5-2 shows some examples of checking the dynamic stress equilibrium for plain and EGC mixtures after removing the time lags, indicating that the sum of incident stress and reflected stress fitted well with the transmission stress during the whole loading process, which suggests the achievement of dynamic stress equilibrium condition.

![Stress vs Time Graphs](image)

Figure 5-2 Examples of typical dynamic stress equilibrium: (a) P0R0 at 139.57 s⁻¹, (b) P2.0R0 at 139.21 s⁻¹ and (c) P1.75R0.25 at 143.85 s⁻¹.

One assumption has been made for the SHPB test, where the stress waves in both incident and transmission bars propagated without any dispersion (i.e., one-dimensional stress wave theory) (Chen and Song, 2011). This theory relates the particle velocity at both ends of the tested specimen to the three aforementioned strain pulses, as shown in Figure 5-3 (where \(C_b\) is the longitudinal wave velocity of the
Based on this, the history of average engineering strain rate ($\dot{\varepsilon}(t)$) and strain ($\varepsilon(t)$) in the tested specimen can be calculated as ($\dot{\varepsilon}$ on the left-hand side is a strain rate, while $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$ on the right-hand side are strains converted to strain rates via the factor of $C_b$ that has a unit of ms$^{-1}$) (Chen and Song, 2011):

$$\dot{\varepsilon}(t) = \frac{v_1 - v_2}{L_s} = \frac{C_b}{L_s}(\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)) \quad (5-1)$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon} \, dt = \frac{C_b}{L_s} \int_0^t (\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)) \, dt \quad (5-2)$$

where $L_s$ is the length of the tested specimen, $\varepsilon_i(t)$ and $\varepsilon_r(t)$ are the incident and reflected strains recorded by strain gauge 1 on the incident bar (see Figure 5-1), and $\varepsilon_t(t)$ is the transmission strain recorded by strain gauge 2 on the transmission bar.

The history of stress ($\sigma(t)$) in the tested specimen can be calculated by averaging the stresses at both ends of the specimen, assuming axial equilibrium of the specimen with the bars at both ends of the specimen, and also assuming the bars remain linear elastic:

$$\sigma(t) = \frac{E_b A_b}{2 A_s} (\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)) \quad (5-3)$$

where $E_b$ and $A_b$ denote the elastic modulus and cross-sectional area of the SHPB bar, respectively, and $A_s$ is the cross-sectional area of the tested specimen.

It should be noted that the specimen strain was calculated from Equation (5-2) and the specimen stress was determined from Equation (5-3).

Figure 5-3 Schematic diagram of testing section of SHPB.

After the SHPB tests, the fibre conditions crossing the fracture interfaces were captured using a portable digital microscope. In addition, to better characterise the fibre morphology in EGCs subjected to high-velocity impacts, SEM scanning (FEI, QUANTA FEG 250, USA) was carried out on some fracture pieces of failed specimens.
5.3 Results and discussion

5.3.1 Dynamic compressive stress-strain response

The stress-strain response is an important index for characterising the dynamic properties of materials and the representative stress-strain curves of all mixtures covering the strain rates from 54.43 s\(^{-1}\) to 164.13 s\(^{-1}\) are presented in Figure 5-4. The strain and stress shown in the curves were obtained using Equation (5-2) and Equation (5-3), respectively. As the strain rate for concrete is not constant during the entire process of dynamic loading (Xiao et al., 2015, Li et al., 2021c) and the strain rate at the failure point (i.e., peak stress) can be considered as the representative strain rate (Pham et al., 2020, Hao and Hao, 2013, Chen et al., 2013), the same approach was employed to define the representative strain rate in this study. As seen, the stress-strain curves of the plain geopolymer mixture and EGCs had similar shapes consisting of ascending and descending stages. During the ascending stage, the stress increases linearly with the rising strain within the elastic region followed by the non-linear stress increment before the peak stress. After reaching the elastic limit, the internal cracks are initiated and progressed with the increase of strain. In the meantime, the fibres in EGCs start to bridge the cracks and restrain the crack growth. Besides, a certain amount of energy is required to de-bond the fibres from the geopolymer matrix and initiate the pull-out of fibres. After exceeding the peak stress, the cracks are further propagated and expanded, leading to visible cracks (Ren et al., 2018, Yu et al., 2021). Furthermore, most of the fibres in EGCs undergo sliding/slippage during the pull-out process up to the final failure of tested specimens. Although a similar shape of stress-strain response can be observed for different mixtures, the resultant values of stress and strain in various stages (e.g., peak stress) were different which will be discussed further in the following sections.

The quadratic curve-fitting method (2\(^{nd}\) order polynomial curve-fitting) was applied to fit the data in Figure 5-4 by assuming the boundary condition: \(\varepsilon = 0, \sigma = 0\) (Yang et al., 2023, Li et al., 2003). Some examples of fitted stress-strain curves and a summary of fitted equations for all mixes are presented in Figure 5-5 and Table 5-1, respectively. The 2\(^{nd}\) order polynomial model can achieve a satisfactory fit of the stress-strain data as the \(R^2\) values of most fitted equations were larger than 0.9. It should be noted that the fitness of the model was better when the strain rate was lower, which is consistent with a previous study (Yang et al., 2023) that the deviation of the
stress-strain data of the wet concrete from the polynomial model was increased with the rising loading rate.
Figure 5-4 Dynamic compressive stress-strain response of all mixtures.

Figure 5-5 Examples of comparison between experimental and curve-fitting results of stress-strain curves.
Table 5-1 Summary of fitted equations for all mixtures.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Strain rate (s(^{-1}))</th>
<th>Fitted equation</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0R0</td>
<td>56.27</td>
<td>(\sigma = -1082094.1\varepsilon^2 + 13692.8\varepsilon)</td>
<td>0.8242</td>
</tr>
<tr>
<td></td>
<td>106.35</td>
<td>(\sigma = -559119.4\varepsilon^2 + 12579.3\varepsilon)</td>
<td>0.9837</td>
</tr>
<tr>
<td></td>
<td>136.23</td>
<td>(\sigma = -362788.7\varepsilon^2 + 11651.9\varepsilon)</td>
<td>0.9737</td>
</tr>
<tr>
<td></td>
<td>157.70</td>
<td>(\sigma = -3799880.9\varepsilon^2 + 13662.2\varepsilon)</td>
<td>0.8596</td>
</tr>
<tr>
<td>P1.0R0</td>
<td>54.43</td>
<td>(\sigma = -1029083.3\varepsilon^2 + 14288.6\varepsilon)</td>
<td>0.9286</td>
</tr>
<tr>
<td></td>
<td>100.81</td>
<td>(\sigma = -609892.1\varepsilon^2 + 13411.8\varepsilon)</td>
<td>0.9291</td>
</tr>
<tr>
<td></td>
<td>138.28</td>
<td>(\sigma = -484341.3\varepsilon^2 + 14089.6\varepsilon)</td>
<td>0.9917</td>
</tr>
<tr>
<td></td>
<td>160.21</td>
<td>(\sigma = -323238.5\varepsilon^2 + 12010.4\varepsilon)</td>
<td>0.9026</td>
</tr>
<tr>
<td>P1.5R0</td>
<td>57.14</td>
<td>(\sigma = -1007269.5\varepsilon^2 + 13928.7\varepsilon)</td>
<td>0.9445</td>
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<tr>
<td></td>
<td>104.36</td>
<td>(\sigma = -555262.6\varepsilon^2 + 12723.1\varepsilon)</td>
<td>0.9037</td>
</tr>
<tr>
<td></td>
<td>140.76</td>
<td>(\sigma = -541598.1\varepsilon^2 + 15734.8\varepsilon)</td>
<td>0.9257</td>
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<tr>
<td></td>
<td>164.13</td>
<td>(\sigma = -397402.5\varepsilon^2 + 14471.3\varepsilon)</td>
<td>0.9090</td>
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<tr>
<td>P2.0R0</td>
<td>55.05</td>
<td>(\sigma = -1145545.2\varepsilon^2 + 15186.9\varepsilon)</td>
<td>0.9301</td>
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<td></td>
<td>103.95</td>
<td>(\sigma = -508969.0\varepsilon^2 + 12141.3\varepsilon)</td>
<td>0.9581</td>
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<td></td>
<td>137.81</td>
<td>(\sigma = -488492.8\varepsilon^2 + 14681.0\varepsilon)</td>
<td>0.9526</td>
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<tr>
<td></td>
<td>162.86</td>
<td>(\sigma = -353751.0\varepsilon^2 + 13094.7\varepsilon)</td>
<td>0.9112</td>
</tr>
<tr>
<td>P1.75R0.25</td>
<td>61.00</td>
<td>(\sigma = -742999.9\varepsilon^2 + 12533.7\varepsilon)</td>
<td>0.9239</td>
</tr>
<tr>
<td></td>
<td>104.77</td>
<td>(\sigma = -575709.3\varepsilon^2 + 13650.0\varepsilon)</td>
<td>0.9734</td>
</tr>
<tr>
<td></td>
<td>139.83</td>
<td>(\sigma = -438558.4\varepsilon^2 + 13947.4\varepsilon)</td>
<td>0.9058</td>
</tr>
<tr>
<td></td>
<td>155.65</td>
<td>(\sigma = -377948.8\varepsilon^2 + 13927.9\varepsilon)</td>
<td>0.7661</td>
</tr>
<tr>
<td>P1.5R0.5</td>
<td>57.88</td>
<td>(\sigma = -1225807.5\varepsilon^2 + 16162.9\varepsilon)</td>
<td>0.9362</td>
</tr>
<tr>
<td></td>
<td>109.64</td>
<td>(\sigma = -682181.9\varepsilon^2 + 14742.2\varepsilon)</td>
<td>0.9753</td>
</tr>
<tr>
<td></td>
<td>144.04</td>
<td>(\sigma = -443451.3\varepsilon^2 + 14053.4\varepsilon)</td>
<td>0.8882</td>
</tr>
<tr>
<td></td>
<td>157.60</td>
<td>(\sigma = -396429.1\varepsilon^2 + 14203.6\varepsilon)</td>
<td>0.8617</td>
</tr>
<tr>
<td>P1.25R0.75</td>
<td>57.39</td>
<td>(\sigma = -1166577.4\varepsilon^2 + 15808.9\varepsilon)</td>
<td>0.9796</td>
</tr>
<tr>
<td></td>
<td>108.59</td>
<td>(\sigma = -554453.1\varepsilon^2 + 12907.8\varepsilon)</td>
<td>0.9741</td>
</tr>
<tr>
<td></td>
<td>140.41</td>
<td>(\sigma = -457960.5\varepsilon^2 + 13561.5\varepsilon)</td>
<td>0.9737</td>
</tr>
<tr>
<td></td>
<td>162.20</td>
<td>(\sigma = -344918.0\varepsilon^2 + 12736.1\varepsilon)</td>
<td>0.8633</td>
</tr>
<tr>
<td>P1.0R1.0</td>
<td>60.09</td>
<td>(\sigma = -784815.6\varepsilon^2 + 12441.4\varepsilon)</td>
<td>0.9118</td>
</tr>
<tr>
<td></td>
<td>107.93</td>
<td>(\sigma = -469239.0\varepsilon^2 + 11300.1\varepsilon)</td>
<td>0.8987</td>
</tr>
<tr>
<td></td>
<td>142.49</td>
<td>(\sigma = -471109.2\varepsilon^2 + 13368.5\varepsilon)</td>
<td>0.9751</td>
</tr>
<tr>
<td></td>
<td>163.11</td>
<td>(\sigma = -411737.5\varepsilon^2 + 13383.4\varepsilon)</td>
<td>0.8696</td>
</tr>
</tbody>
</table>
5.3.2 Failure pattern

5.3.2.1 Effect of strain rate

Figures 5-6 and 5-7 demonstrate the typical failure patterns of all mixtures at various strain rates, indicating that the damage degree and integrity loss of all mixtures were increased with the increasing strain rate. At a low strain rate (56.27 s\(^{-1}\)), the plain geopolymer mixture (P0R0) exhibited prominent longitudinal splitting failure with several fragments with irregular sizes (Figure 5-6a). When the strain rate raised, the damage on P0R0 became more severe with more and smaller fragments. The crack velocity tended to be lower at a low strain rate, which allowed the cracks to go through the weak zones to propagate from the edge of the specimen towards its core area (Yu et al., 2021, Fu et al., 2018). Thus, several large fragments can be observed for the failed specimen. As the strain rate increased, the applied stress and crack velocity went up rapidly to generate more cracks to consume the energy before the cracks had sufficient time to seek the weak zone to propagate (Wang et al., 2018, Yu et al., 2021) as crack generation requires more energy than crack propagation. Hence, the specimen fractured into more fragments with smaller sizes at a high strain rate.

5.3.2.2 Effect of fibre

As seen in Figures 5-6b-d, the incorporation of PVA fibres reduced the damage degree of specimens under various strain rates compared to P0R0 (Figure 5-6a). When the strain rate was lower (54.43-104.36 s\(^{-1}\)), P1.0R0, P1.5R0 and P2.0R0 maintained the cylindrical shapes of specimens along with some visible edge cracks after the dynamic compression due to the bridging effect of fibres that can effectively prevent the matrix from breaking into fragments and improves the impact resistance. Similar findings were reported for steel fibre reinforced and PVA fibre reinforced geopolymer composites (Khan et al., 2018a, Xiao et al., 2021). As the strain rate increased to about 140 s\(^{-1}\), all PVA fibre reinforced EGC specimens started to disintegrate and presented fragmental failure, while fewer fragments with larger sizes can be found if the PVA fibre dosage was high (Figure 5-6d). With the further increase of strain rate to about 160 s\(^{-1}\), more fragments with irregular sizes can be observed for all PVA fibre reinforced EGCs, mainly due to the less bridging fibres across the cracking interfaces induced by the increased crack size at a high strain rate (Wu et al., 2017). More fibres were either pulled out or ruptured under high-velocity impact loads.
Figure 5-6 Typical failure patterns of plain mixture and mono-PVA fibre reinforced EGCs at different strain rates.

As displayed in Figure 5-7, all hybrid fibre reinforced EGCs had similar failure patterns with P2.0R0 at different strain rates. When the strain rate exceeded approximately 140 s\(^{-1}\), replacing PVA fibres with more RTP fibres (0.75\% and 1.0\%) tended to be less resistant to impact with a larger integrity loss (Figures 5-7c and d). Given the length difference between PVA and RTP fibres, RTP fibres would be more effective in bridging the initiated internal micro-cracks while when the micro-cracks grew into macro-cracks, PVA fibres started to exert the crack-arresting ability. Fewer RTP fibres can be found in bridging the crack interfaces of failed specimens as they were mostly pulled out with the crack development. Thus, when an appropriate content of PVA fibres is replaced with RTP fibres, the synergistic effects of them can lead to better impact behaviour compared to the mono-PVA fibre reinforced EGC. Besides, fibre-matrix bonding and fibre orientation also play essential roles in reducing the damage degree of EGCs after dynamic compression (Yu et al., 2021). Considering fibre orientation, inconsistent conclusions can be found in the literature revealing that
better impact resistance can be achieved when fibres are distributed either parallel (Groeneveld et al., 2018) or perpendicular (Huang et al., 2021) to the loading direction. Given the different failure patterns here, fibres oriented perpendicular to the loading direction could be more effective in bridging and restraining the longitudinal splitting cracks along the edge of the specimen and the transverse cracks around the centre surface of the specimen. The failure patterns discussed above can only be used to qualitatively assess the impact resistance of materials while the quantitative analysis will be given below.

![Typical failure patterns of hybrid fibre reinforced EGCs at different strain rates.](image)

**Figure 5-7** Typical failure patterns of hybrid fibre reinforced EGCs at different strain rates.

5.3.3 Dynamic compressive strength

5.3.3.1 Effect of strain rate

*Figure 5-8* demonstrates the dynamic compressive strength of all mixtures at different strain rates, which indicates that all mixtures exhibited a similar feature that the dynamic compressive strength was enhanced with the increase of strain rate. For instance, the dynamic compressive strength of P0R0 was increased by 31-116% when
the strain rate changed from 56.27 s\(^{-1}\) to 106.35 s\(^{-1}\), 136.23 s\(^{-1}\) and 157.7 s\(^{-1}\), respectively, which can be ascribed to the structural effects (lateral inertia and end friction confinement), time-dependent crack propagation effect and Stefan effect induced by the viscosity of free water (Hao et al., 2013, Lai and Sun, 2009, Ren et al., 2015). The lateral inertia effect arises as the lateral deformation of the tested specimen under a high-speed impact loading (due to Poisson’s effect) is confined by the backward inertia force (Hao et al., 2013). The end friction confinement effect is caused by the friction at the specimen-SHPB bar interface, constraining the lateral deformation of the tested specimen and thereby improving its strength. As mentioned in Section 5.2, some approaches have been applied to mitigate these structural effects. Besides, it was reported that a significant lateral inertia effect only appears when the strain rate is over 200 s\(^{-1}\) (Zhang et al., 2009b). Thus, it can be assumed that the strength enhancement observed in this study can be mainly caused by the crack propagation effect (see Section 5.3.2) and the Stefan effect. Regarding the Stefan effect, the free water between cracks would create a viscous force to hinder the crack propagation under high-velocity impact loading (i.e., improving the strength) instead of generating a wedging effect to favour the crack propagation at a low strain rate (Fu et al., 2018, Fu et al., 2021). The viscous force tends to be higher at a higher crack velocity (larger strain rate) which can further enhance the dynamic compressive strength of specimens. Besides, the meniscus effect of free water could lead to the enhancement of the dynamic compressive strength of EGCs (Rossi, 1991).

![Figure 5-8](image)

Figure 5-8 Effects of strain rate and fibre on dynamic compressive strength of EGCs.
5.3.3.2 Effect of fibre

Unlike the quasi-static compressive strength, the addition of PVA fibres increased the dynamic compressive strength of geopolymers. For instance, as seen in Figure 5-8, within the strain rate of 100.81-109.64 s⁻¹, the dynamic compressive strengths of P1.0R0, P1.5R0 and P2.0R0 were 7%, 12% and 17% higher than that of P0R0. The crack propagation under quasi-static loading is similar to that under dynamic loading at a low strain rate, where the cracks can go through the weak zones to propagate. As discussed in previous chapters, the porosity of the EGC can be higher due to the additional air entrapped by PVA fibres, and thus fewer fibres can offer bridging effects under quasi-static loading as the cracks tend to propagate through the induced voids caused by the fibres (Ranjbar and Zhang, 2020). As mentioned previously, the crack velocity raised with the increasing strain rate and more cracks were generated before the cracks had enough time to reach the weak zones. Meanwhile, more PVA fibres can exert their effects to bridge and restrain the induced cracks. Different from the plain geopolymer, an additional amount of energy was required to pull out or rupture the fibres in EGCs. Hence, the dynamic compressive strength can be improved by the bridging effect of PVA fibres under various strain rates, which is consistent with the findings reported in Refs. (Fu et al., 2018, Zhang et al., 2022) that polypropylene fibre reinforced concrete had comparable or lower quasi-static compressive strength but higher dynamic compressive strength under various strain rates (25-125 s⁻¹) than plain concrete.

In addition, the fibre-matrix interface properties would also strongly affect the dynamic compressive properties of EGCs. Compared to other synthetic fibres, PVA fibres possess special interface characteristics in terms of chemical bonding, frictional bonding and slip-hardening coefficient (Redon et al., 2001), which are related to the microstructure and properties of the matrix, e.g., fracture toughness (Zhang et al., 2020c) (see Section 2.3.2). To facilitate the pull-out process of PVA fibre, the applied stress should first overcome the chemical bonding to de-bond the fibre from the matrix followed by the slippage/sliding of the fibre governed by the frictional bonding and slip-hardening coefficient (Li, 2019). Moderate frictional bonding and slip-hardening coefficient are desirable to induce fibre pull-out instead of fibre rupture. It was found that the interface properties between PVA fibre and matrix can be improved with the increasing strain rate (Curosu et al., 2016, Yang and Li, 2014). Besides, the mechanical properties of PVA fibres (e.g., tensile strength) can be enhanced with the increase of
strain rate. For instance, the tensile and bond strengths of PVA fibres were enhanced by about 55% and 64%, respectively, when the loading displacement velocity changed from 0.005 mm/s to 50 mm/s (Curosu et al., 2016). These combined effects can cause an increased number of pulled out PVA fibres as the strain rate rises, leading to an increase in dynamic compressive strength of EGCs. This finding can be detected in Figure 5-9a that more PVA fibres were pulled out instead of ruptured under dynamic loading, which is in good agreement with a previous study (Trindade et al., 2020) demonstrating that the failure mode of PVA fibre in the EGC changed from fibre rupture under quasi-static loading to fibre pull-out under dynamic loading. Hence, the strength improvement of PVA fibre reinforced EGCs over P0R0 was found to rise with the increase of strain rate up to about 140 s⁻¹. For instance, the dynamic compressive strengths of P2.0R0 at the strain rates of 55.05 s⁻¹, 103.95 s⁻¹ and 137.81 s⁻¹ were found to be 6.8%, 17% and 19% higher than that of P0R0 under similar strain rates (Figure 5-8). However, as the strain rate went up to around 160 s⁻¹, the strength improvement ratio of PVA fibre reinforced EGCs over P0R0 declined. For instance, the dynamic compressive strength of P2.0R0 was only 9.1% higher than that of P0R0, which can be ascribed to the increased crack width and superior fibre-matrix interface properties. Due to the excellent interface properties, the probability of PVA fibre rupture tended to be higher, which would reduce the fibre bridging efficiency. Many ruptured PVA fibres can be observed at the strain rate of around 160 s⁻¹ (Figure 5-9b). Overall, all PVA fibre reinforced EGCs exhibited a higher dynamic compressive strength compared to plain geopolymer mixture under different strain rates, where P2.0R0 indicated the best performance.
Figure 5-9 Fibre conditions at the cracking interfaces after dynamic compressive loading.

As illustrated in Figure 5-8, partial replacement of PVA fibres with RTP fibres can result in a slightly higher or comparable dynamic compressive strength compared to the EGC containing 2.0% PVA fibre. For instance, the dynamic compressive strengths of P1.75R0.25 at strain rates of 61 s\(^{-1}\), 104.77 s\(^{-1}\), 139.83 s\(^{-1}\) and 155.65 s\(^{-1}\) were 3.6%, 5.3%, 2.3% and 0.62%, respectively greater than that of P2.0R0 under similar strain rates. Besides, P1.5R0.5 showed a comparable dynamic compressive strength to P2.0R0 with a difference of no more than 3.4%. Like PVA fibre, the mechanical and interface properties of the RTP fibre could be improved with the increase of strain rate. As discussed in previous chapters, the use of hybrid PVA fibre and a small amount of RTP fibre in the EGC can lead to desirable fibre orientation and the synergistic effect of hybrid fibres at different scales can be effectively employed to bridge and restrain
the induced cracks under dynamic loadings. As shown in Figure 5-9c, RTP fibres were mostly pulled out due to their shorter lengths while longer PVA fibres can better provide the crack-resistance action as the cracks developed. Furthermore, the fibre spacing of RTP fibres in EGCs tended to be smaller compared to that of PVA fibres due to the shorter length under a given volume of fibre reinforcement (Chen et al., 2021a). As such, more RTP fibres can contribute to the bridging effect around a single micro-crack to prevent it from further growth and coalescence into a macro-crack and thus improve the impact resistance of EGCs. EGCs with RTP fibres could contain more free water than PVA fibre reinforced EGCs due to the release of temporarily blocked liquid at the surface of RTP fibres (Serdar et al., 2015), which would lead to an improvement in dynamic compressive strength due to the Stefan effect (Fu et al., 2021). The interface properties of RTP fibre at a higher strain rate were still significantly lower as compared with PVA fibre due to the inherent hydrophobic surface feature of RTP fibre, as displayed in Figures 5-9a and c that more matrix fragments were adhered on the PVA fibre surfaces, while RTP fibres had smooth surfaces with fewer attached matrix fragments. Therefore, with the substitution of RTP fibre (0.75-1.0%) for PVA fibre in the EGC, a 4.2-13% reduction in dynamic compressive strength can be observed in comparison with P2.0R0. To conclude, most hybrid fibre reinforced EGC mixtures can outperform the plain geopolymer mixture in terms of dynamic compressive strength and adding a small amount of RTP fibre into the EGC is beneficial to the dynamic compressive strength mainly because of the synergistic effect of hybrid fibres in arresting and controlling the cracks.

5.3.4 Dynamic increase factor

5.3.4.1 Effect of strain rate

DIF is defined as the ratio of dynamic compressive strength to quasi-static compressive strength. Acquiring a reliable relationship between DIF and strain rate can better characterise the strain rate sensitivity of materials under high-velocity impact loads and can offer more insights for future structural design and numerical study. To this end, the experimental scatters of DIF and strain rate were used to develop the DIF equations for all mixtures, the results of which are illustrated in Figure 5-10. As reported by previous studies (Khan et al., 2018a, Chen et al., 2019, Chen et al., 2021b), the compressive DIF of fibre reinforced concrete was linearly proportional to the logarithm of strain rate. Hence, this fitting approach has been used in this study. As seen in Figure 5-10, the transition strain rate was considered, which divided the
proposed DIF equations into two parts (Khan et al., 2018a, Hao and Hao, 2013, Yang et al., 2018). It was reported that the strength improvement of materials as the change of strain rate is not pronounced below the transition strain rate while over which, the strength would go up considerably (Yang et al., 2018). The DIF of all mixtures was improved significantly with the increasing strain rate after exceeding the transition strain rate ranging from 56.15 s\(^{-1}\) to 67.51 s\(^{-1}\), which can be due to the reasons explained for dynamic compressive strength (see Section 5.3.3).
5.3.4.2 Effect of fibre

When the fibre content changed, the variation of transition strain rate was not consistent. Khan et al. (2018a) found that the transition strain rate of fibre reinforced geopolymer composites was 66 s⁻¹ which was higher than that of plain geopolymers (30 s⁻¹). This can be ascribed to the reduced lateral deformation as a result of the fibre bridging behaviour, leading to a higher triggering rate to change the properties of composites (Wang et al., 2011a). In addition, the transition strain rate can be affected by the combined effect of fibre content, fibre shape and matrix strength (Yang et al., 2018). The developed first-part DIF equations of P0R0, P1.0R0 and P1.0R1.0 had lower reliability considering their $R^2$ values. By contrast, other proposed first-part DIF equations were more reliable due to their higher $R^2$ values (mostly larger than 0.9). In general, to further increase the reliability of the first-part DIF equations and better understand the transition strain rate, more DIF data at the low strain rates especially intermediate strain rates ($10^{-3}$-1 s⁻¹) are required.

Regardless of fibre type and content, the presence of fibres enhanced the strain rate sensitivity of geopolymers given that the second-part DIF equations of EGC mixtures had higher gradients ranging from 2.559 to 3.178 in comparison with P0R0, which can be ascribed to the additional resistance provided by the fibres under dynamic loadings. This is in good agreement with previous studies on geopolymer composites (Khan et al., 2018a, Xiao et al., 2021). For instance, it was found that the DIF of geopolymer composites containing 1.2% PVA fibre was increased by 3.56-4.25 times as compared with plain geopolymers under similar impact velocities (Xiao et al., 2021). Similar to dynamic compressive strength, the strain rate sensitivity of the EGC was improved with the increase of PVA content while the strain rate sensitivity was reduced when the RTP fibre content was over 0.25%. P1.75R0.25 exhibited the highest strain rate...
sensitivity among all mixtures and the strain rate sensitivity of P1.5R0.5 was comparable with that of P2.0R0. The mechanisms behind these were similar to those provided in Section 5.3.3. This further suggests that replacing PVA fibres with a small amount of RTP fibres can lead to better dynamic compressive properties. The proposed second-part DIF equations of all mixtures shown in Figure 5-10 had high reliability as most of the \( R^2 \) values were greater than 0.9.

5.3.4.3 Comparison with existing models

Figure 5-11 shows the DIF results obtained from this study in comparison with the predictions using the existing DIF models (CEB-FIP model code 1990: Design code, 1990, FIB Model Code for Concrete Structures, 2013) and the results obtained from literature on geopolymer composites (Khan et al., 2018a, Xiao et al., 2021). The DIF models proposed by FIB and CEB-FIP have high accuracy and reliability for normal-strength concrete with a transition rate of 30 s\(^{-1}\):

\[
DIF_{\text{FIB}} = \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} \right)^{0.014} \text{ for } \dot{\varepsilon} \leq 30 \text{ s}^{-1}
\]

\[
DIF_{\text{FIB}} = 0.012\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} \right)^{1} \text{ for } \dot{\varepsilon} > 30 \text{ s}^{-1}
\]

\[
DIF_{\text{CEB-FIP}} = \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} \right)^{1.026\alpha} \text{ for } \dot{\varepsilon} \leq 30 \text{ s}^{-1}
\]

\[
DIF_{\text{CEB-FIP}} = \gamma\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_1} \right)^{1} \text{ for } \dot{\varepsilon} > 30 \text{ s}^{-1}
\]

where \( \dot{\varepsilon}_1 \) is equal to 0.00003 s\(^{-1}\), \( \alpha \) is \((5 + 9 \frac{f_c}{f_{c1}})^{-1}\), \( \gamma \) is \(10^{(6.156\alpha - 2)}\), \( f_c \) is the quasi-static compressive strength, and \( f_{c1} = 10 \text{ MPa} \).

The above equations indicate that the FIB model code ignores the quasi-static compressive strength while the CEB-FIP model code has taken it into account. In this study, 50 MPa was selected as the input of the CEB-FIP model. The predicted results of DIF using the above models were higher than the results obtained from this study when the strain rate was less than 100 s\(^{-1}\), which can be attributed to the lower transition strain rates of the models proposed by FIB and CEB-FIP. The differences between them were reduced with the increasing strain rate. It is worth noting that when the strain rate reached about 160 s\(^{-1}\), the DIF of the plain geopolymer mixture was comparable to that predicted by the models while all EGCs exhibited higher DIF values. On the other hand, at a higher strain rate (e.g., 140 s\(^{-1}\)), the mixtures containing solely synthetic fibres possessed higher DIF values than the mixtures containing steel.
fibres, implying a lower strain rate sensitivity for steel fibre reinforced composites. Similar results have been reported in Refs. (Ren et al., 2018, Lai and Sun, 2009), which can be ascribed to the superior internal quality of steel fibre reinforced composites with lower porosity and fewer internal flaws as concrete with poorer quality can lead to higher DIF under dynamic loadings (Bischoff and Perry, 1991, Ren et al., 2018, Yang et al., 2018). Moreover, the lower strain rate sensitivity of steel itself compared to the matrix may contribute to the smaller DIF values (Su et al., 2016).

Figure 5-11 Comparison of DIF obtained from this study with that predicted using currently existing models (CEB-FIP model code 1990: Design code, 1990, FIB Model Code for Concrete Structures, 2013) and that acquired from existing studies (Xiao et al., 2021, Khan et al., 2018a).

5.3.5 Energy absorption capacity

5.3.5.1 Effect of strain rate

The energy absorption capacity of all mixtures under dynamic loadings can be represented by the area under the entire stress-strain curve shown in Figure 5-4, the results of which are presented in Figure 5-12 considering the effects of strain rate and fibre. As discussed in Section 5.3.1, the energy absorption capacity of the mixture is significantly increased after the elastic stage as the generation and propagation of cracks as well as the fibre pull-out (for EGCs only) mainly appear after reaching the elastic limit. Consistent with dynamic compressive strength and DIF, the energy absorption capacity of all mixtures was considerably enhanced with the increasing strain rate. For instance, the energy absorption capacity of P2.0R0 was increased by 157%, 388% and 552% when the strain rate raised from 55.05 s\(^{-1}\) to 103.95 s\(^{-1}\), 137.81 s\(^{-1}\) and 162.86 s\(^{-1}\), respectively. This can be partially due to the improved dynamic
compressive strength as a result of the combined action of time-dependent crack propagation and Stefan effect. It should be noted that the energy absorption considered in this study is not only affected by strength but also strain (deformation). As seen in Figure 5-4, the strain at the peak stress of all mixtures known as peak strain was mostly improved with the increase of strain rate as a result of the enhanced cumulative strain at the appearance of more cracks (Li et al., 2021c), which contributes to the overall improvement of energy absorption capacity.

Figure 5-12 Effects of strain rate and fibre on energy absorption capacity of EGCs.

5.3.5.2 Effect of fibre

The SEM images of PVA and RTP fibres in EGCs are presented in Figures 5-13 and 5-14, respectively, which can provide more details about the fibre surface condition after dynamic loadings and help interpret the test results above. As pointed out above, the presence of fibres was beneficial to the energy absorption capacity of geopolymers under various strain rates. Within the strain rate range of 54.43-109.64 s⁻¹, increasing the PVA fibre content from 1.0% to 2.0% did not obviously improve the energy absorption capacity of the EGC, which can be ascribed to the insignificant improvement in dynamic compressive strength caused by the increased PVA fibre dosage under these strain rates (Figure 5-8). As mentioned earlier, the increase of strain rate can improve the mechanical and interface properties of PVA fibres, which facilitates the fibre pull-out rather than fibre rupture. Thus, within the strain rate range of 136.23-144.04 s⁻¹, the energy absorption capacity of P2.0R0 was the highest among all mono-PVA fibre reinforced EGCs, which was 11% and 2.9% higher than that of
P1.0R0 and P1.5R0, respectively. More pulled out PVA fibres can be observed along with some pronounced traces after PVA fibre pull-out (Figures 5-13a and b). However, with the further increase of strain rate, the energy absorption capacity of the EGC was not improved as the PVA dosage increased from 1.5% to 2.0%, which can be associated with the reduced fibre efficiency (see Section 5.3.3). As seen in Figure 5-13d, due to the considerably high interface properties of PVA fibre, it ruptured when the applied stress exceeded its tensile strength during the pull-out process, which can weaken the energy absorption capacity as fibre pull-out can absorb more energy than fibre rupture (Zhao et al., 2020). Besides, fibres tend to rupture when their inclination angles are too large.

Replacing PVA fibre with a certain amount of RTP fibre (0.25-0.5%) led to a better or comparable energy absorption capacity as compared with P2.0R0. For instance, the energy absorption capacity of P1.75R0.25 was 5.1-31% higher than that of P2.0R0 under various strain rates. This can be primarily attributed to the enhanced dynamic compressive strength caused by the synergistic effect between PVA and RTP fibres in controlling the cracks, smaller fibre spacing of RTP fibres and possibly increased free water content. Additionally, the flexible feature of RTP fibre can enhance its efficiency in bridging and restraining cracks (Figure 5-14a). Although the increase of strain rate may improve the mechanical and interface properties of RTP fibre, it still exhibited pull-out behaviour due to the intrinsic hydrophobic feature, which can be identified in Figure 5-14. As seen in Figure 5-13c and Figure 5-14b, the RTP fibre’s surface had fewer attached matrix fragments as compared with PVA fibre. Under compressive loading with a high strain rate, the pull-out behaviour of RTP fibre can compensate for the loss of energy absorption capacity induced by the ruptured PVA fibre. Therefore, substituting a small amount of RTP fibre for PVA fibre in the EGC can help enhance its energy absorption capacity. Lu et al. (2018b) found a similar phenomenon that replacing PVA fibres with recycled PET fibres led to a comparable energy absorption capacity in comparison with composites containing 2.0% PVA fibre because of the larger number of pulled out PET fibres under impact loading. On the other hand, due to the lower dynamic compressive strength, P1.25R0.75 and P1.0R1.0 exhibited poorer energy absorption capacity than P2.0R0. Within the strain rate range of 136.23-164.13 s\(^{-1}\), the energy absorption capacities of P1.25R0.75 and P1.0R1.0 were found to be even smaller than that of P0R0 due to their smaller peak strain values and comparable dynamic compressive strengths compared to P0R0 within the
aforementioned strain rate range (Figure 5-8). It was observed that the incorporation of fibres does not vary the peak strain considerably (Yu et al., 2021, Wu et al., 2017, Ren et al., 2018), while the peak strain is more relevant to the strain rate. Moreover, due to the incomplete fracture of some EGC mixtures, the evaluated energy absorption capacity may be slightly underestimated compared to P0R0 (Khan et al., 2018a). Overall, P1.75R0.25 and P1.5R0.5 can outperform P0R0 in terms of energy absorption capacity.

Figure 5-13 SEM images of fibre morphology in mono-PVA fibre reinforced EGC after dynamic compressive loading.

Figure 5-14 SEM images of fibre morphology in hybrid fibre reinforced EGC after dynamic compressive loading.
Figure 5-15 illustrates the schematic failure mechanism of the hybrid fibre reinforced EGC under dynamic compression. At a lower strain rate, only some oblique cracks appear inside the EGC, and the cracks can propagate along the weak zones. Because of the synergistic effect of PVA and RTP fibres in restraining the cracks, the mixture can maintain its structural integrity. As the strain rate increases, more cracks arise owing to the increased crack velocity and the mixture starts exhibiting fragmental failure. Herein, RTP fibres can effectively restrain the growth of initiated micro-cracks, and PVA fibres can bridge and control the larger cracks.

![Figure 5-15 Schematic illustration of failure pattern after dynamic compressive loading.](image)

5.4 Summary

In this chapter, the effects of PVA fibre content (1.0%, 1.5% and 2.0%) and RTP fibre dosage (0.25%, 0.5%, 0.75% and 1.0%) on the dynamic compressive behaviour of EGCs under various strain rates of 54.43-164.13 s\(^{-1}\) were investigated. Based on the experimental results, the main conclusions can be drawn as follows:

- The dynamic compressive behaviour including dynamic compressive strength, DIF, failure degree and energy absorption capacity of all mixtures was sensitive to strain rate. The strain rate dependency can be well described using the proposed DIF equations with \(R^2\) values of mostly greater than 0.9 for the considered strain rates ranging from \(10^{-5}\) s\(^{-1}\) to \(10^3\) s\(^{-1}\). The DIF of EGCs obtained from the current study was lower than the predicted DIF by the existing models for Portland cement concrete when the strain rate was lower than 100 s\(^{-1}\), but larger when the strain rate was around 160 s\(^{-1}\).

- The incorporation of either PVA or RTP fibres can mostly improve the dynamic compressive strength, DIF, and energy absorption capacity and can all reduce the
post-test damage degree of geopolymers mainly due to the additional resistance induced by the fibre bridging effect. Utilising a small amount of RTP fibre (e.g., 0.25%) to replace PVA fibre in EGCs can lead to a better dynamic compressive strength, DIF and energy absorption capacity as compared with the mono-PVA fibre reinforced EGC.

- SEM images indicate that more pulled out PVA fibres can be identified under dynamic loading, which was favourable for enhancing the dynamic compressive properties, especially energy absorption capacity. However, the possibility of PVA fibre rupture increased at the strain rate of 155.65-164.13 s⁻¹, which can weaken the energy absorption capacity. RTP fibres still exhibited pull-out behaviour under dynamic loadings, resulting in an enhanced energy absorption capacity of EGCs containing RTP fibres at various strain rates.

- The EGC containing 1.75% PVA fibre and 0.25% RTP fibre can be regarded as the optimal mixture considering its highest dynamic compressive properties at various strain rates among all studied mixtures.
Chapter 6 Dynamic splitting tensile behaviour of EGCs

6.1 Introduction

Besides dynamic compressive behaviour, it is also crucial to explore the dynamic tensile behaviour of EGCs as concrete structures may fail more easily in tension when subjected to dynamic loadings, e.g., earthquake and explosive blast (Yoo and Banthia, 2019, Malvar and Ross, 1998). This chapter investigates the dynamic splitting tensile behaviour of EGCs with hybrid PVA fibre (1.0-2.0%) and RTP fibre (0-1.0%) at various strain rates (10^{-1} s^{-1} to 10^{1} s^{-1}). The failure pattern, dynamic splitting tensile stress-displacement response, dynamic splitting tensile strength, DIF and energy absorption capacity were analysed and discussed in detail. Furthermore, the microstructural images at the fracture surfaces were used to explore the underlying mechanisms of the fibre bridging effects under dynamic splitting tension. Part of this chapter has been presented in the following peer-reviewed journal paper: Zhong, H. & Zhang, M. (2022) Dynamic splitting tensile behaviour of engineered geopolymer composites with hybrid polyvinyl alcohol and recycled tyre polymer fibres. Journal of Cleaner Production 379:134779.

6.2 Test methods

Similar to Chapter 5, the raw materials and mix proportions used in this chapter are the same as those in Chapter 3. Up to now, the direct tension approach has been mainly used to characterise the dynamic tensile behaviour of EGCs (Farooq et al., 2022, Trindade et al., 2020). Nevertheless, it is difficult to achieve the dynamic stress equilibrium during the loading process (Chen et al., 2014). Employing an indirect tension, i.e., dynamic splitting tensile test using a SHPB, can address the above concern that can provide more reliable results. In addition, the test setup and sample preparation are simpler in comparison with the direct tension approach (Khan et al., 2019). Therefore, the SHPB apparatus (see Figure 5-1) was utilised to explore the tensile behaviour of EGCs under various strain rates in this study. The SHPB configuration and test specimen size (Figure 6-1) were the same as those for the dynamic compressive test. Similarly, the striker impacted the incident bar under the action of compressed nitrogen with different pressure levels (0.4-0.8 MPa) to produce an incident pulse during the SHPB test. When the incident pulse propagated to the interface between the incident bar and the tested sample, a proportion of the incident pulse was reflected as reflected pulse because of the mismatch of wave impedance.
(Chen and Song, 2011), and the remaining pulse continued to propagate along the transmission bar named transmission pulse. The strain gauges mounted on the incident and transmission bars were employed to collect these pulses, i.e., $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$. Besides, a pulse shaper with a diameter of 30 mm and a thickness of 3 mm was used to achieve the dynamic stress equilibrium. Figure 6-2 depicts an example of verifying the stress equilibrium of the tested sample, indicating that the sum of incident pulse and reflected pulse was close to the transmission pulse during the dynamic splitting tension, which confirms the attainment of the equilibrium stress state.

According to the one-dimension elastic stress wave theory, the dynamic splitting tensile stress history ($\sigma_{dt}(t)$) and relative displacement history of the two ends of the tested sample along the loading direction ($u(t)$) can be calculated as (Chen and Song, 2011, Wu et al., 2014):

$$
\sigma_{dt}(t) = \frac{2F_{dt}(t)}{\pi D_s L_s} \\
F_{dt}(t) = \frac{E_s A_b}{2} (\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)) \\
u(t) = C_b \int_0^t (\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)) \, dt
$$

(6-1)

where $F_{dt}(t)$ is the average dynamic splitting tensile force history acting on the tested specimen and $D_s$ denotes the diameter of the tested specimen.

For each test, $\dot{\varepsilon}$ was derived using the following equation (Hao and Hao, 2016, Khan et al., 2019):

$$
\dot{\varepsilon} = \frac{f_{dt}}{t_0 E_s}
$$

(6-2)

where $f_{dt}$ corresponds to the dynamic splitting tensile strength, $t_0$ represents the time needed to achieve the peak of transmission stress, and $E_s$ is the elastic modulus of the tested specimen.

The energy absorption capacity of the tested sample during dynamic splitting tension ($W_{dt}$) can be calculated by (Chen et al., 2020a):

$$
W_{dt} = E_s A_b C_b \int_0^t (\varepsilon_i^2(t) - \varepsilon_r^2(t) - \varepsilon_t^2(t)) \, dt
$$

(6-3)

To detect the fibre failure morphology after SHPB tests, a portable digital microscope and SEM equipment (FEI, QUANTA FEG 250, USA) were applied. For SEM imaging, several small pieces of EGC samples after dynamic splitting tension were carefully extracted and then used for scanning.
6.3 Results and discussion

6.3.1 Failure pattern

6.3.1.1 Effect of strain rate

The typical failure modes of all mixtures under various strain rates are presented in Figures 6-3 and 6-4. In general, similar to the failure specimens under dynamic compression (Section 5.3.2), the failure patterns of all mixtures here were strain-rate dependent. As mentioned early, the major crack should mostly pass through the centre of the specimen whilst the splitting tensile loading. However, as seen in Figure 6-3a, the plain geopolymer exhibited pronounced fragmental failure when the strain rate was within 0.94-2.77 s\(^{-1}\). More small fragments can be identified near the two ends of specimens. For instance, at the strain rate of 0.94 s\(^{-1}\), two large and almost symmetric fragments can be seen within the central portion of the specimen, implying that the first visible crack occurred at the centre of the specimen and then started propagating towards the two ends. Due to the possibly increased stress concentration at the loading interfaces and the high brittleness of the plain mixture (Chen et al., 2017), more macro-cracks can be generated during the propagation of the splitting crack. Therefore, when the strain rate was higher, the plain geopolymer exhibited fragmental failure instead of
one vertical splitting crack passing through the centre. Similar findings were reported in previous studies (Zhao et al., 2020, Li et al., 2020b).

Figure 6-3 Typical failure patterns of plain geopolymer and mono-PVA fibre reinforced EGCs.

A similar change of failure pattern with strain rate can be observed for EGC specimens. When the strain rate was lower (2-3.2 s$^{-1}$), the failure patterns of all EGC mixtures were similar to those after the quasi-static splitting tension, where the major splitting cracks were still bridged by the fibres. As the strain rate increased, all specimens started to disintegrate into two halves along with some spalling pieces, debris or diffuse cracks. This can be ascribed to the increased crack velocity, which can increase the crack formation and propagation rates and thus induce more micro-cracks and reduce the fibre bridging efficiency. In addition, some EGC mixtures exhibited triangular damage near the two ends of specimens at a strain rate over 4 s$^{-1}$, as seen in Figure 6-3c. Similar phenomena were found in previous studies (Chen et al., 2020a, Khan et al., 2019, Li et al., 2020b), which can be attributed to the limited crack
initiation and development along the loading diameter as a result of the increased stress concentration near two ends.

![Images of failure patterns](image)

Figure 6-4 Typical failure patterns of hybrid fibre reinforced EGCs.

6.3.1.2 Effect of fibre

As displayed in Figures 6-3 and 6-4, irrespective of fibre type and content, the inclusion of fibres significantly reduced the damage degree of samples at different strain rates as all EGC samples did not show the fragmental failure observed in plain geopolymer. When the PVA fibre dosage within the specimen was higher, the damage level caused by the dynamic splitting tension was lower. At a strain rate of 2-3.2 $s^{-1}$, P1.0R0 fractured into almost two halves along with a very tiny number of fibres bridging the major splitting crack (Figure 6-3b), while the crack width of the splitting crack for P1.5R0 was much smaller and more bridging PVA fibres appeared at the crack interface (Figure 6-3c). The integrity loss of P2.0R0 was the lowest as compared with P1.0R0 and P1.5R0, which can be ascribed to the higher number of effective bridging fibres at the crack interface (Lai et al., 2022, Khan et al., 2019). As mentioned in the last section, all mono-PVA fibre reinforced EGC mixtures were broken into two
halves at a higher strain rate but the increase of PVA fibre dosage still can mitigate the damage. For instance, the failed sample of P1.0R0 had many spalling pieces and debris, while P1.5R0 and P2.0R0 did not show such phenomenon under a similar strain rate. However, altering the PVA fibre dosage did not have an apparent effect on reducing the triangular damage degree of specimens, especially within a strain rate of 5.2-7.38 s\(^{-1}\). A similar finding was reported in previous studies that increasing either steel fibre content (Khan et al., 2019, Hao and Hao, 2016) or RTP fibre dosage (Chen et al., 2020a) in cementitious or geopolymer materials did not considerably mitigate the triangular damage near the loading ends.

Figure 6-4 indicates that the failure patterns of all hybrid fibre reinforced EGCs were comparable with that of the EGC incorporating 2.0% PVA fibre at different strain rates as no significant spalling pieces and debris were identified. This can be ascribed to the synergistic effect of hybrid fibres in limiting cracks, as discussed previously. Less diffuse cracks can be distinguished on the failed EGC specimens at a higher strain rate because of the larger fracture propagation rate. Therefore, most fibres did not have enough time to disperse the splitting tensile stress as they were either pulled out or ruptured quickly as the growth of the major splitting crack. Overall, the presented failure modes here can reveal the positive influence of fibres in enhancing the dynamic splitting tensile behaviour as compared with plain geopolymer, while it should be further verified with quantitative analyses below.

6.3.2 Dynamic splitting tensile strength

6.3.2.1 Effect of strain rate

Figure 6-5 displays the typical dynamic splitting tensile stress against relative displacement for all mixtures at different strain rates. All curves had a similar shape consisting of ascending and descending stages. Within the ascending region, the dynamic splitting tensile stress would first increase linearly with the increase of relative displacement before moving into the non-linear stress increment stage. The first visible crack usually appears during this non-linear region (Lai et al., 2022). Then, the crack would propagate towards two ends of the specimen, and the fibres start exerting their crack-controlling functions for EGC mixtures.
The dynamic splitting tensile strength (i.e., peak dynamic splitting tensile stress) of all mixtures was sensitive to the strain rate. For instance, the dynamic splitting tensile strength of P2.0R0 was enhanced by 78% and 100% when the strain rate increased from 3.2 s\(^{-1}\) to 6.2 s\(^{-1}\) and 7.38 s\(^{-1}\), respectively. This can be mainly attributed to the increased crack velocity, Stefan effect and lateral inertia (Khan et al., 2019, Chen et al., 2014). As mentioned in Section 6.3.1.1, the enhanced crack velocity induced by the increase of strain rate would lead to higher crack initiation and proliferation rates, which can be evidenced by Figure 6-5 that the slope of the curve was larger at a higher strain rate. More micro-cracks are generated to consume the energy, improving the strength. For the Stefan effect, the reaction force caused by the free water trapped between the crack is proportional to the crack velocity (Chen et al., 2014), which would contribute to the strength improvement as the increase of strain rate. Although it was reported that using the specimen with an aspect ratio of 0.5 for the SHPB test can eliminate the inertia effect (Khan et al., 2018a, Bertholf and Karnes, 1975), these findings were mainly valid for the dynamic compression test. Therefore, the observed strength enhancement here could be partly caused by the lateral inertia effect.

**6.3.2 Effect of fibre**

The effects of PVA and RTP fibres on the dynamic splitting tensile strength of EGCs at different strain rates are shown in Figure 6-6. Similar to quasi-static splitting tensile strength, the presence of fibres significantly enhanced the dynamic splitting tensile strength of geopolymers at various strain rates. For instance, the dynamic splitting tensile strengths of P2.0R0 and P1.0R1.0 were 155% and 120% higher than...
that of P0R0 within a strain rate of 0.94-3.2 s\(^{-1}\). The dynamic splitting tensile strength of the EGC tended to be larger when the PVA fibre dosage was higher. At a strain rate of 4.34-6.2 s\(^{-1}\), the dynamic splitting tensile strength of P2.0R0 was 12\% and 31\% higher than that of P1.5R0 and P1.0R0, which can be ascribed to the enhanced fibre bridging behaviour at the crack interface. Under dynamic loading, the mechanical properties of PVA fibres and the bonding between fibres and matrix were enhanced with the rising strain rate (Yang and Li, 2014, Curosu et al., 2016), which would improve the fibre bridging efficiency and resulted in more pulled out PVA fibres. Thus, a more obvious strength enhancement of mono-PVA fibre reinforced EGCs over plain geopolymer under dynamic loading can be found than that under quasi-static loading. Nevertheless, inconsistent results were observed in this study. For instance, the quasi-static splitting tensile strength of P1.5R0 was about 169\% higher than that of P0R0, while the corresponding dynamic splitting tensile strength was only 129-144\% greater. This is because the crushing damage on plain geopolymer was more significant in comparison with EGC mixtures (see Figure 6-3a), which would overestimate its dynamic splitting tensile strength. Furthermore, the strength enhancement of mono-PVA fibre reinforced EGCs over plain geopolymer declined slightly when the used nitrogen pressure level changed from 0.6 MPa to 0.8 MPa, which can be associated with the increased number of ruptured PVA fibres caused by the superior interface properties of PVA fibres at a higher strain rate and thereby weakening the fibre bridging efficiency. In addition, fibres tend to rupture when their inclination angles are too large (Li, 2019).

On the other hand, replacing PVA fibre with a small dosage of RTP fibre (0.25-0.5\%) resulted in comparable or slightly better dynamic splitting tensile strength compared to P2.0R0 (no more than 3.4\% difference between them). Under quasi-static loading, the splitting tensile strength of P1.75R0.25 was 3.4\% lower than that of P2.0R0, while P1.75R0.25 outperformed P2.0R0 in terms of dynamic splitting tensile strength when the strain rate was within 1.79-7.38 s\(^{-1}\). This can be mainly ascribed to the improved synergistic effect of hybrid fibres in restraining the cracks under dynamic loading caused by the increased fibre properties and better fibre distribution. The smaller spacing between RTP fibres can contribute to the improved efficiency of such synergistic effect (Chen et al., 2019). Because of the hydrophobic feature of RTP fibres, more free water may be retained within the matrix of the EGC. As such, the Stefan effect can be intensified to improve strength. Nevertheless, when the RTP fibre
replacement level was higher than 0.5%, the dynamic splitting tensile strengths of P1.25R0.75 and P1.0R1.0 were 7.9-10% and 13-15% lower than that of P2.0R0 under different strain rates. This is because RTP fibres are more efficient in controlling the micro-cracks. When these micro-cracks grow into macro-cracks, fewer PVA fibres can arrest and bridge them as the total number of PVA fibres is lower at a higher RTP fibre replacement level. Besides, the fibre distribution of these EGC mixtures could be poorer as a result of lower workability, which can weaken the synergistic effect of hybrid fibres and thus strength.

![Graph showing the dynamic splitting tensile strength of EGCs vs. strain rate.](image)

**Figure 6-6** Effects of strain rate and fibre on dynamic splitting tensile strength of EGCs.

**Figure 6-7** shows the fibre conditions at the crack interface under dynamic splitting tension. Similar to the fibre conditions under quasi-static loading, both pulled out and ruptured PVA fibres can be captured when the strain rate was lower, and most fibres still bridged the crack (**Figure 6-7a**). By contrast, when the strain rate was higher, almost no fibres bridged the crack due to the increasing crack width. Many pulled out PVA fibres with a long pull-out length can be identified. Although the ruptured PVA fibre still can be found, it can be assumed that its total proportion was smaller than that at a lower strain rate, which is consistent with the finding reported in a previous study (**Trindade et al., 2020**) that most PVA fibres in the EGC were pulled out under dynamic tension. As seen in **Figure 6-7b**, there was no pronounced change in terms of the RTP fibre failure condition with the change of strain rate, implying that RTP fibres still presented a pull-out feature though their properties were also enhanced with strain rate.

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Fewer bridging RTP fibres can be observed near the crack interface at a lower strain rate, which confirms the previous discussion that RTP fibres are not effective in restraining the macro-cracks. To this end, the dosage of RTP fibre in EGCs should be limited to ensure the acceptable crack-controlling ability for hybrid fibre reinforced EGCs under dynamic loading.

Figure 6-7 Fibre conditions under dynamic splitting tension.

6.3.3 Dynamic increase factor

6.3.3.1 Effect of strain rate

Figure 6-8 illustrates the proposed DIF equations for all studied mixtures, indicating that a transition rate existed for all mixtures. After that, DIF went up considerably with the increasing strain rate, which is consistent with the changing trend of dynamic splitting tensile strength with strain rate. It is worth mentioning that the transition rates for all EGC mixtures (2.09-3.28 s\(^{-1}\)) were higher than that for plain geopolymer (1.03 s\(^{-1}\)), which can be ascribed to the larger activating rate required for fibre reinforced composites to alter their properties as a result of fibre bridging
behaviour (Wang et al., 2011a). The resulted strain rate for plain geopolymer was lower than that for EGCs under the same nitrogen pressure level. A similar finding was presented in a previous study (Lai et al., 2022) that the obtained strain rate for plain concrete was slightly lower than that for the mixtures containing steel fibres or rubber particles mainly due to the changes of elastic modulus and density. Given the equation for calculating the strain rate, i.e., Equation (6-2), it can be found that the determined strain rate can be strongly affected by elastic modulus. Overall, the developed DIF equations here had high reliability with $R^2$ of mostly greater than 0.9.

6.3.3.2 Effect of fibre

The plain geopolymer was more sensitive to strain rate as indicated in the largest gradient of the proposed first-part equation (see Figure 6-8a). The serious crushing damage on plain geopolymer can overestimate its dynamic splitting tensile strength, leading to a higher strength enhancement rate. Additionally, as seen in Figures 6-3 and 6-4, most EGC mixtures maintained the structural integrity with many bridging fibres at the crack interfaces when the strain rate was within 2-3.2 s$^{-1}$, which can considerably restrain the formation of micro-cracks, weakening the strain rate sensitivity. Similar results were found in previous studies (Khan et al., 2019, Lai et al., 2022). The moisture content plays an essential role in the region between the quasi-static strain rate and transition strain rate (Wu et al., 2012), which can explain why hybrid fibre reinforced EGCs had higher strain rate sensitivity (with a gradient of over 0.07) than mono-PVA fibre reinforced EGCs (with a gradient of 0.061-0.067) in this region (see Figures 6-8b-h). When the strain rate exceeded the transition strain rate, P2.0R0 and other hybrid fibre reinforced EGC mixtures possessed a more significant strain rate dependence than plain geopolymer and other mono-PVA fibre reinforced EGC mixtures, implying that the fibre bridging and pull-out behaviour play an important role in enhancing the strain rate sensitivity during this region. It was also found in a previous study (Hao and Hao, 2016) that the pull-out behaviour of spiral steel fibres significantly improved the strain rate sensitivity of normal concrete.
Figure 6-8 Relationship between DIF and strain rate for all mixtures.
6.3.3.3 Comparison with existing models

Figure 6-9 demonstrates a comparison of the obtained DIF results in this study with the predictions by the existing DIF models for cementitious materials. The DIF model proposed by CEB-FIP has been widely used to describe the strain rate effect on the strength rise of normal concrete up to 300 s\(^{-1}\):

\[
\begin{aligned}
DIF_{\text{CEB-FIP}} &= \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_2} \right)^{1.016 \alpha_1} \text{ for } \dot{\varepsilon} \leq 30 \text{ s}^{-1} \\
DIF_{\text{CEB-FIP}} &= \gamma_1 \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_2} \right)^{\frac{1}{3}} \text{ for } \dot{\varepsilon} > 30 \text{ s}^{-1}
\end{aligned}
\]  

(6-4)

where \( \dot{\varepsilon}_2 \) is equal to 0.000003 s\(^{-1}\), \( \alpha_1 \) is \((10 + 6 \frac{f_c}{f_{c1}})^{-1}\), and \( \gamma_1 = 10^{(7.11\alpha - 2.33)}\).

It can be seen that the CEB-FIP model takes the quasi-static compressive strength into account, and 50 MPa was used as the input. Later on, Malvar and Ross (1998) found that the CEB-FIP model was not reliable for estimating the strain rate sensitivity of normal concrete at high strain rates and thus proposed a new model with a lower transition rate, as follows:

\[
\begin{aligned}
DIF_{\text{M&RS}} &= \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_3} \right)^{\alpha_2} \text{ for } \dot{\varepsilon} \leq 1 \text{ s}^{-1} \\
DIF_{\text{M&RS}} &= \gamma_2 \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_3} \right)^{\frac{1}{3}} \text{ for } \dot{\varepsilon} > 1 \text{ s}^{-1}
\end{aligned}
\]  

(6-5)

where \( \dot{\varepsilon}_3 \) is equal to 0.000001 s\(^{-1}\), \( \alpha_2 \) is \((1 + 8 \frac{f_c}{f_{c1}})^{-1}\), and \( \gamma_2 = 10^{(6\alpha - 2)}\).

The FIB model was also used for comparison:

\[
\begin{aligned}
DIF_{\text{FIB}} &= \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_3} \right)^{0.018} \text{ for } \dot{\varepsilon} \leq 10 \text{ s}^{-1} \\
DIF_{\text{FIB}} &= 0.0062 \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_3} \right)^{\frac{1}{3}} \text{ for } \dot{\varepsilon} > 10 \text{ s}^{-1}
\end{aligned}
\]  

(6-6)

The DIF results of EGC mixtures at the strain rate of 2.3 s\(^{-1}\) were close to the FIB model, while the results at higher strain rates fitted the Malvar-Ross model well. By contrast, the DIF result of plain geopolymer at the strain rate of 0.94 s\(^{-1}\) showed a good agreement with the Malvar-Ross model, while the results tended to deviate from all models presented in Figure 6-9 when the strain rate increased. The discrepancy between the measured DIF results and predictions by CEB-FIP and FIB models at a strain rate of over 4 s\(^{-1}\) can be ascribed to the unreliability of CEB-FIP model under high strain rates (Malvar and Ross, 1998) and the ignorance of quasi-static compressive strength in FIB model. The above three models were developed mainly based on the data of normal concrete. The microstructure and macroscopic behaviour
of investigated mixes in this study were different from those of normal concrete (e.g., shrinkage and porosity), leading to some inconsistencies between model predictions and the obtained DIF results here, especially for plain geopolymer mortar. For instance, the shrinkage of plain geopolymer mortar would be greater than that of normal concrete due to the absence of coarse aggregate, which may cause more cracks generated under dynamic loading and thereby higher DIF values as opposed to normal concrete, especially at a higher strain rate. The DIF results of EGCs under both ambient temperature curing and heat curing obtained from Farooq et al. (2022) did not fit all the models shown in Figure 6-9. The heat-cured EGCs had higher DIF values (1.86-2.2) than the ambient-cured EGCs (1.57-1.86) when the strain rate was around 0.51 s⁻¹, due to the higher brittleness induced by cracking as a result of shrinkage. The DIF values of ambient-cured EGCs obtained by Farooq et al. (2022) were greater than the measured data in this study under a similar strain rate, which can be attributed to the different testing methods adopted to measure the dynamic tensile strength as well as disparate macroscopic properties, e.g., quasi-static compressive and tensile strengths.

Figure 6-9 Comparison of DIF obtained from this study with that predicted using currently existing models (FIB Model Code for Concrete Structures, 2013, CEB-FIP model code 1990: Design code, 1990, Malvar and Ross, 1998) and that acquired from the existing study (Farooq et al., 2022).

6.3.4 Energy absorption capacity

6.3.4.1 Effect of strain rate

Figure 6-10 presents the energy absorption capacity of all mixtures, which was determined as per the law of conservation of energy. The changing trend of energy absorption capacity was consistent with that of dynamic splitting tensile strength and
DIF with strain rate. For instance, the energy absorption capacity of P0R0 was improved by 201% and 357% when the strain rate altered from 0.94 s\(^{-1}\) to 1.79 s\(^{-1}\) and 2.77 s\(^{-1}\), respectively. Such energy enhancement with the increasing strain rate was strongly associated with the dynamic splitting tensile strength and can be mainly attributed to the growing appearance of micro-cracks and rapid proliferation of main splitting cracks (Zhao et al., 2020, Chen et al., 2020a, Lai et al., 2022).

![Figure 6-10 Effects of strain rate and fibre on energy absorption capacity of EGCs.](image)

6.3.4.2 Effect of fibre

Unlike plain geopolymer, an extra part of energy was required for EGCs to pull out or rupture the fibres during the SHPB test. As seen in Figure 6-10, the presence of fibres significantly enhanced the energy absorption capacity of geopolymers under different strain rates. When the strain rate was within 1.79-6.2 s\(^{-1}\), the energy absorption capacity of P1.0R0, P1.5R0, P2.0R0, P1.75R0.25, P1.5R0.5, P1.25R0.75 and P1.0R1.0 was 159%, 166%, 201%, 199%, 205%, 164% and 159% higher than that of P0R0. The increase of PVA fibre dosage led to a higher energy absorption capacity for the EGC due to the increased number of fibres experiencing the pull-out process (Kanda and Li, 1998), which shows a good agreement with the dynamic splitting tensile strength (see Figure 6-6). Regarding the effect of RTP fibres, EGC mixtures containing RTP fibres outperformed the EGC reinforced with 2.0% PVA fibre in terms of the energy absorption capacity when the strain rate was within 2-3.2 s\(^{-1}\). For instance, the energy absorption capacity of P1.75R0.25 and P1.5R0.5 was 17% and 1.9% higher than that of P2.0R0. As discussed in Section 6.3.2, ruptured PVA fibres can be found
at a lower strain rate, weakening the energy absorption capacity as pulled out PVA fibres are more favourable for absorbing energy. Regardless of strain rate, RTP fibres still exhibited the pull-out behaviour, which can compensate for the energy loss caused by the ruptured PVA fibres. Nevertheless, such compensation tended to be insignificant as the strain rate increased. It is worth noting that P1.75R0.25 still can exhibit comparable energy absorption with P2.0R0, which is consistent with a previous study (Lu et al., 2018b) that replacing PVA fibres with hydrophobic PET fibres can lead to similar energy absorption capacity for the ECC compared to that with 2.0% PVA fibre.

Figure 6-11 illustrates some SEM micrographs of PVA and RTP fibre conditions after the dynamic splitting tension test, which can offer more insights into the effect of fibre on the energy absorption capacity. It should be noted that these SEM images were taken on the samples after being subjected to the impact force with a nitrogen pressure level of 0.8 MPa. More pulled out PVA fibres can be found along with several pull-out traces and abrasion traces on the surfaces of fibres, which coincide with those shown in Figure 6-7a that the fibres can considerably improve the energy absorption capacity of EGCs. Owing to the strong interface properties, some ruptured PVA fibres still can be captured, which can impair the energy absorption capacity of EGCs. RTP fibre still exhibited pull-out behaviour due to its weak bond with the matrix, which can be evidenced by its smooth surface. This fibre pull-out behaviour can recompense for the loss of energy absorption as a result of the ruptured PVA fibres at a lower strain rate, while such positive effect may vanish when the crack width and size become more prominent.
Figure 6-11 SEM micrographs of fibre conditions under dynamic splitting tension.

Figure 6-12 demonstrates the schematic failure mechanism of the hybrid fibre reinforced EGC under dynamic splitting tension. Only one major splitting crack appears for the hybrid fibre reinforced EGC after dynamic splitting tension, which is not pronounced at a lower strain rate. Meanwhile, many bridging fibres can be observed at the crack interface. As the strain rate rises, the crack width of the splitting crack becomes more extensive with noticeable triangular damage sections at two ends, where most fibres are pulled out or ruptured under this situation. Due to the synergistic fibre effect, smaller RTP fibre spacing, Stefan effect and pull-out behaviour of RTP fibre at different strain rates, the dynamic splitting tensile properties of hybrid fibre reinforced EGCs can slightly surpass the mono-PVA fibre reinforced EGC.
6.4 Summary

In this chapter, the indirect tension approach was performed to investigate the effects of different fibres including PVA and RTP fibres on the dynamic splitting tensile properties of EGCs. Based on the experimental results, the main conclusions can be listed as follows:

• The incorporation of PVA or RTP fibres significantly enhanced the dynamic splitting properties and reduced the damage level of geopolymers. The dynamic splitting tensile strength and energy absorption capacity of the EGC were consistently improved with the increase of PVA fibre content, while replacing PVA fibre with 0.25-0.5% RTP fibre can slightly enhance the dynamic splitting tensile properties compared to the EGC with 2.0% PVA fibre.

• The failure pattern, dynamic splitting tensile strength, DIF and energy absorption capacity of all mixtures were strain-rate dependent, which can be well described using the proposed equations. The DIF of all mixes in this study did not fit the currently existing DIF models for Portland cement concrete, especially at a higher strain rate.

• More pulled out PVA fibres can be identified under dynamic loading due to the increased fibre properties with the change of strain rate, which is beneficial for the dynamic splitting tensile properties. Because of the inherent hydrophobic feature, the failure mode of RTP fibre did not change with strain rate, which can recompense for the loss of energy absorption induced by the ruptured PVA fibres but can impair the dynamic splitting tensile strength when the dosage of RTP fibre in the EGC exceeded 0.5%.
Chapter 7 Conclusions and perspectives

In this thesis, the feasibility of using RTP fibres to partly replace the commonly used PVA fibres to improve the sustainability of FA-GGBS based EGCs and retain acceptable engineering properties was explored based on a series of experimental tests. The effects of various PVA and RTP fibre dosages on the static and dynamic mechanical properties of EGCs were systematically studied. The tensile strain-hardening behaviour of EGCs was verified using the micromechanics design theory and the fibre bridging mechanisms under different loadings were explored based on the microstructural investigation. The main research contributions and conclusions are given as follows.

7.1 Research contributions

The following contributions have been made to complement the existing knowledge of the engineering properties of FA-GGBS based EGCs cured at ambient temperature:

- The effects of different PVA fibre contents (1.0%, 1.5% and 2.0%) and RTP fibre replacement dosages (0.25%, 0.5%, 0.75% and 1.0%) on the workability, setting time, static and dynamic mechanical properties as well as material cost and sustainability of FA-GGBS based EGCs were systematically investigated, which can help obtain the optimal mixtures that can achieve the desired performance.

- Both micromechanical analysis and microstructural investigation were conducted to get a thorough understanding of the PVA and RTP fibre effects on the uniaxial tensile behaviour of EGCs.

- The results of the dynamic mechanical properties of EGCs can provide new insights into the effects of mono-PVA fibre and hybrid PVA-RTP fibre on the dynamic compressive and splitting tensile behaviour under a wide range of strain rates (10^0 to 10^3 s^-1). Some empirical equations describing the relationships between DIF and strain rate were proposed for all studied EGC mixes to better predict the dynamic mechanical behaviour of EGCs made from FA and GGBS.

- The newly developed hybrid fibre reinforced EGCs can become sustainable alternatives to ECCs with either PVA or PE fibres because of the lower carbon footprint and energy consumption and can be served as a good example of adopting industrial by-products and recycled tyre materials as secondary resources in construction materials, contributing to building a green society.
7.2 Conclusions

According to the experimental results, the main conclusions can be drawn as follows:

(i) Uniaxial tensile behaviour of proposed EGCs

- EGCs containing 1.5% PVA fibre, 2.0% PVA fibre, or 1.75% PVA fibre and 0.25% RTP fibre fulfilled the strength-based and energy-based criteria for robust tensile strain-hardening behaviour considering the micromechanical characteristics. The uniaxial tensile properties of the EGC consisting of tensile strength, tensile strain capacity and tensile strain energy were increased with the increase of PVA fibre dosage but were weakened when PVA fibres were replaced with RTP fibres.

- Considering the microstructure of EGCs after uniaxial tensile loading, more pulled out PVA fibres were observed at the fracture surface which was favourable for the enhancement of tensile properties of EGCs. By contrast, a weaker bond was identified at the interface between RTP fibre and geopolymer matrix, leading to poor tensile behaviour of EGCs.

- Compared to RTP fibres, the addition of PVA fibres can result in higher porosity for the EGC. No significant difference was found regarding the average fibre inclination angle between the EGC incorporating 2.0% PVA fibre and the EGC containing 1.75% PVA fibre and 0.25% PVA fibre. Nevertheless, the fibre distribution of the hybrid fibre reinforced EGC was better, which was beneficial to some engineering properties.

(ii) Basic engineering properties of proposed EGCs

- In comparison with plain geopolymers, the presence of either PVA or RTP fibres did not improve the workability, compressive strength and elastic modulus of specimens. Replacing 0.25% PVA fibre with RTP fibre can mitigate the loss of the above properties for the EGC caused by the addition of 2.0% PVA fibre. Overall, all EGC mixes presented acceptable workability, setting time and 28-d compressive strength.

- The drying shrinkage of the EGC was significantly reduced with the increasing PVA fibre content (up to 1.5%) and RTP fibre replacement dosage. The splitting tensile strength of geopolymers was enhanced by about 129-196% in the presence
of fibres and the structural integrity of EGC samples was retained instead of the brittle failure observed for plain geopolymers.

- The material cost and embodied energy of EGCs were decreased by around 9-35% and 4-16%, respectively, when RTP fibres were used to substitute PVA fibres. The carbon footprint of all EGC mixes in this research was substantially lower than that of typical ECC mixtures.

(iii) Dynamic mechanical properties of proposed EGCs

- The dynamic compressive and splitting tensile properties including dynamic compressive strength, dynamic splitting tensile strength, DIF, failure degree and energy absorption capacity of the plain geopolymer and EGCs were considerably improved with the increase of strain rate. The proposed equations describing the relationships between DIF and strain rate can well describe the strain rate dependency of all mixes.

- The presence of PVA or RTP fibres can mostly significantly improve both dynamic compressive and splitting tensile properties and can all decrease the post-test damage degree of geopolymers. Replacing a small amount of RTP fibre (0.25-0.5%) to replace PVA fibre in EGCs can result in better or comparable dynamic mechanical properties, primarily associated with the synergistic effect of hybrid fibre in controlling cracks, the RTP fibre spacing and the Stefan effect.

- SEM micrographs indicate that more pulled out PVA fibres can be observed after dynamic loadings because of the improved fibre properties and bonding behaviour, which largely contributed to the improvement of dynamic mechanical properties. Due to the hydrophobic surface feature of RTP fibres, their failure mode did not change with strain rate, which can compensate for the loss of energy absorption capacity caused by the rupture of PVA fibres.

(iv) Optimal hybrid fibre reinforced EGCs

- The EGC with 1.75% PVA fibre and 0.25% RTP fibre can be considered as the optimal mixture as in comparison with the EGC with 2.0% PVA fibre, it had better dynamic mechanical properties, lower material cost and higher sustainability. In addition, it possessed acceptable workability, setting time and quasi-static mechanical properties especially exhibiting robust tensile strain-hardening behaviour. The RTP fibre replacement dosage should not exceed 0.5%.
7.3 Perspectives

Considering the experimental results of the current thesis, the limitations and the following recommendations for future research are suggested.

• In this thesis, the commonly used NaOH and Na$_2$SiO$_3$ solutions were used as alkaline activators for preparing EGCs. Nevertheless, these activators have some potential issues. For instance, the problem of efflorescence can happen due to the reaction between the excess alkali and the atmospheric CO$_2$. Besides, using a large amount of Na$_2$SiO$_3$ solution would still lower the sustainability of EGCs. Hence, alternative activators with lower alkali and higher sustainability such as Na$_2$CO$_3$ and Na$_2$SO$_4$ should be considered for the development of sustainable EGCs.

• In this research, the adopted RTP fibres were provided by the same company while their properties such as composition can vary with the used tyre type and recycling process. Besides, the efficiency of RTP fibres inside EGCs would be affected by the cleaning method and process of as-received RTP fibres. The current research has adopted a small-scale cleaning method to separate the impurities and rubber particles from the RTP fibres, while a more effective and reliable cleaning method and procedure should be developed for large-scale applications.

• Based on the experimental results of this thesis, the dynamic mechanical properties of EGCs can be significantly affected by the strain rate. Although some empirical equations were proposed to estimate the relationship between DIF and strain rate, more DIF data at different strain rates especially intermediate strain rates are required to develop a more reliable model. Thus, a numerical study should be performed to understand the effect of various strain rates on the DIF of EGCs.

• This thesis has focused on the mechanical properties of EGCs while their durability performance was not considered. Thus, more studies on the durability of EGCs under various mechanical and environmental loadings as well as chemical attacks are needed. The developed hybrid fibre reinforced EGCs are promising to be used in various applications such as the repair and retrofitting of concrete structures, and a feasibility study on these applications is recommended for future research.
The life cycle inventory data of each ingredient of EGCs used in the current research was obtained from the existing studies. However, it is important to conduct a systematic life cycle assessment (cradle-to-grave) using the up-to-date environmental data of each ingredient to further understand the environmental impact of EGCs.
List of Publications

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