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Review of Recent Developments in Tensile Properties of Engineered Geopolymer Composites

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Abstract: ***Engineered Cementitious Composite (ECC) is a type of highly ductile cementitious material. However, due to its characteristics of high energy consumption and high carbon emissions, it is necessary to seek a new type of low-carbon and environmentally friendly substitute. Engineered Geopolymer Composite (EGC), as a promising construction material for replacing ECC, has broad application prospects. Through visual analysis of the relevant literature in Web of Science, it was discovered that the research on EGC mainly concentrates on aspects such as the types of precursors, the chemical composition of the alkali-activated solution, and the related parameters of fibers. This paper mainly combines the relevant experimental research data on the tensile properties of EGC conducted by scholars at home and abroad, and focuses on analyzing the influence of precursor types, the chemical composition of the alkaline activator, and fibers on the tensile properties of EGC. The statistical results indicate that fly ash and ground granulated blast-furnace slag (GGBFS) are the most commonly used precursor materials. Replacing an appropriate amount of fly ash in the precursor with GGBFS can significantly enhance the tensile strength of EGC. The type of alkaline activator and its molarity have a relatively obvious influence on the tensile properties of EGC. An increase in the molarity of NaOH within a certain range can enhance the tensile strength of EGC. Furthermore, the incorporation of fibers, especially synthetic fibers such as polypropylene (PP) and polyvinyl alcohol (PVA) fibers, as well as inorganic fibers such as glass fibers (GF) and carbon fibers (CF), can effectively enhance the tensile strength and tensile strain capacity of EGC. The use of hybrid fibers may further improve the tensile properties.***

Keywords: Engineered geopolymer composites, Tensile properties, Precursor, Alkaline activator, Fiber reinforcement.

1. Introduction

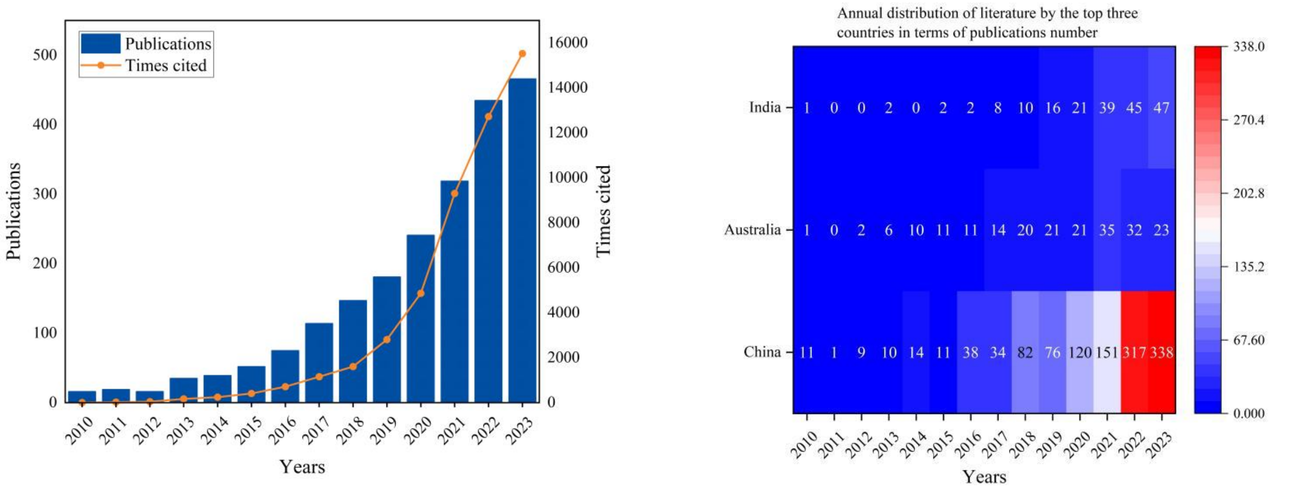
Engineered Cementitious Composite (ECC) is a mortar composite material reinforced with a small amount of discontinuous fibers (typically with a volume rate of ≤ 2%). One characteristic of ECC is its strain-hardening behavior, especially under tensile and bending actions, where numerous fine cracks appear, thereby enhancing plasticity, toughness, and fracture energy. However, to achieve these superior properties, the ECC mix typically requires 2-3 times higher cement content than ordinary Portland cement (OPC) mixes, resulting in high costs and a high carbon footprint [1]. Given the urgent need for green, low-carbon, and sustainable development, exploring environmentally friendly alternatives to ECC is particularly important.

One possible alternative is to use geopolymers instead of cement to produce ECC. Studies have shown that the energy required for geopolymer production is 30% less than that for OPC production, and carbon dioxide emissions are reduced by 80% [2], making geopolymers a low-carbon alternative to OPC. Existing research has also found that geopolymer concrete (GPC) has comparable or better mechanical and durability properties to OPC concrete.

Despite the many advantages of GPC, the material itself is very brittle, which makes it very susceptible to cracking [3]. Therefore, engineered geopolymer composite(EGC), also known as engineered geopolymer concrete, has been proposed to address the high brittleness of geopolymers and reduce the carbon footprint of ECC. Figure 1 shows the annual publication and citation counts of papers related to EGC in the Web of Science, and the number of papers and research on EGC is increasing year by year. The top three countries with the highest number of EGC-related papers are China, Australia, and India.

To gain a more comprehensive understanding of the research hotspots of EGC and the main factors influencing the performance of EGC, a scientific mapping analysis was conducted on the EGC-related literature in the Web of Science based on keywords, as shown in Figure 2. Common terms were excluded from the analysis, and similar keywords were merged. The scientific mapping indicates that the most common research materials in EGC studies are "fly ash", "slag", and "metakaolin". Additionally, the keywords related to experimental testing include "mechanical properties", "compressive strength", and "tensile strength". The statistical results also reveal that the fibers frequently used in EGC are "steel fibers" (SF), "polyethylene (PE) fibers", and "polyvinyl alcohol (PVA) fibers".

Therefore, the main factors influencing the performance of EGC comprise the type of precursor, the chemical composition of the alkali-activated solution, and fiber-related parameters. This paper will integrate the relevant experimental research data on the tensile properties of EGC carried out by domestic and foreign scholars, and focus on the statistical analysis of the related factors influencing the tensile properties of EGC, which can offer certain references for further studies on EGC in the future.



(a) Annual number of publications and citations of papers related to EGC

(b) Annual distribution of literature by the top three countries in terms of publications number

Figure 1: The annual publication volume and citation count of EGC-related papers throughout the years

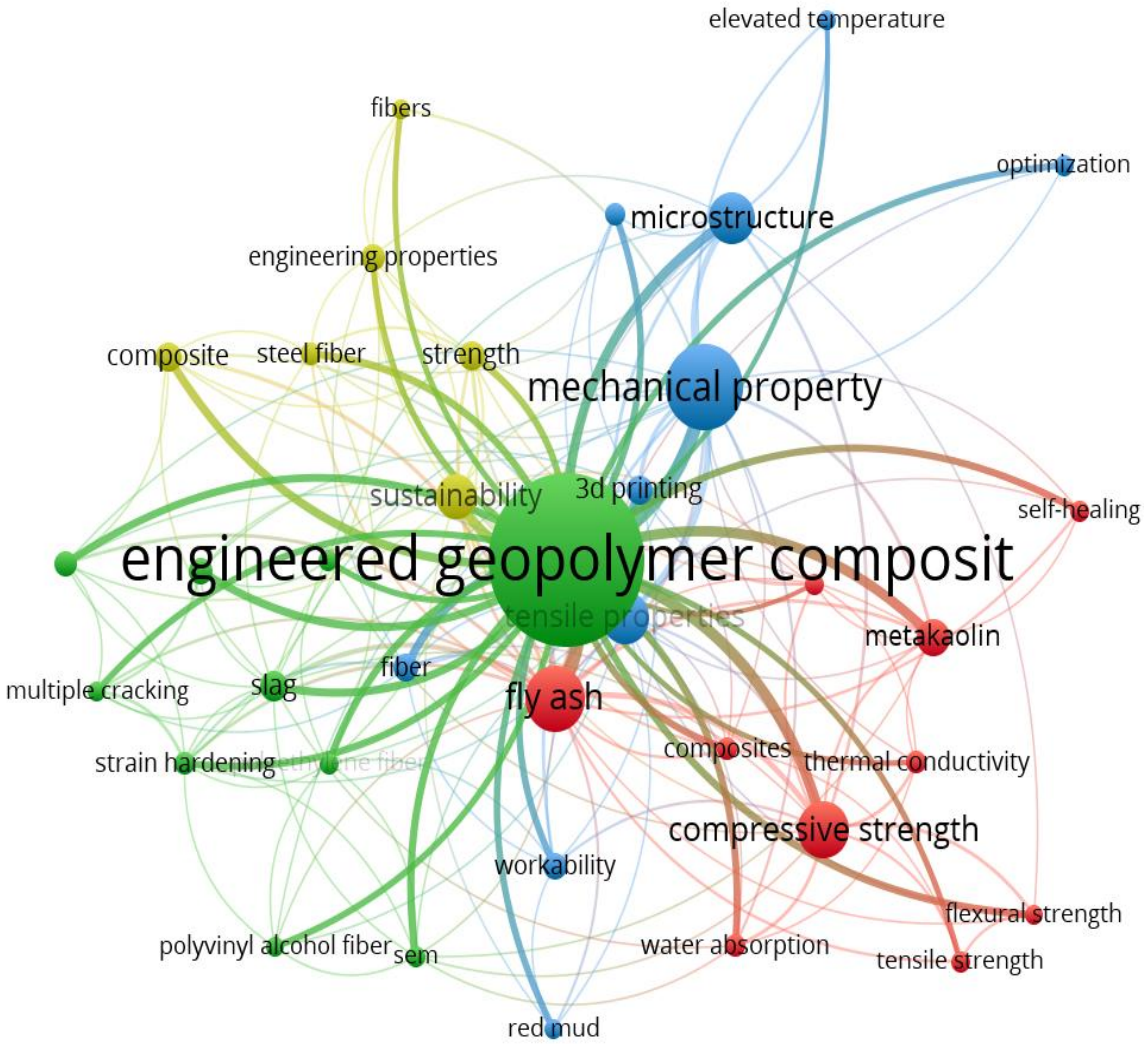


Figure 2: Science mapping based on keywords

2. Engineered Geopolymer Composite

"Geopolymer" was initially proposed by Joseph Davidovits in the 1970s [4] and was regarded as a subset of alkali-activated binders. It is a type of ceramic-like material featuring an amorphous to semi-crystalline three-dimensional aluminosilicate structure. After raw materials rich in silicon (Si) and aluminium (Al) are activated by a mixed alkaline solution, the dissolved AlO_4 and SiO_4 tetrahedra combine by sharing an oxide (O) atom to form monomers. The monomers interact to form oligomers and subsequently synthesize a three-dimensional network of aluminosilicate structure [5]. The geopolymerization chemical process is depicted in Figure 3.

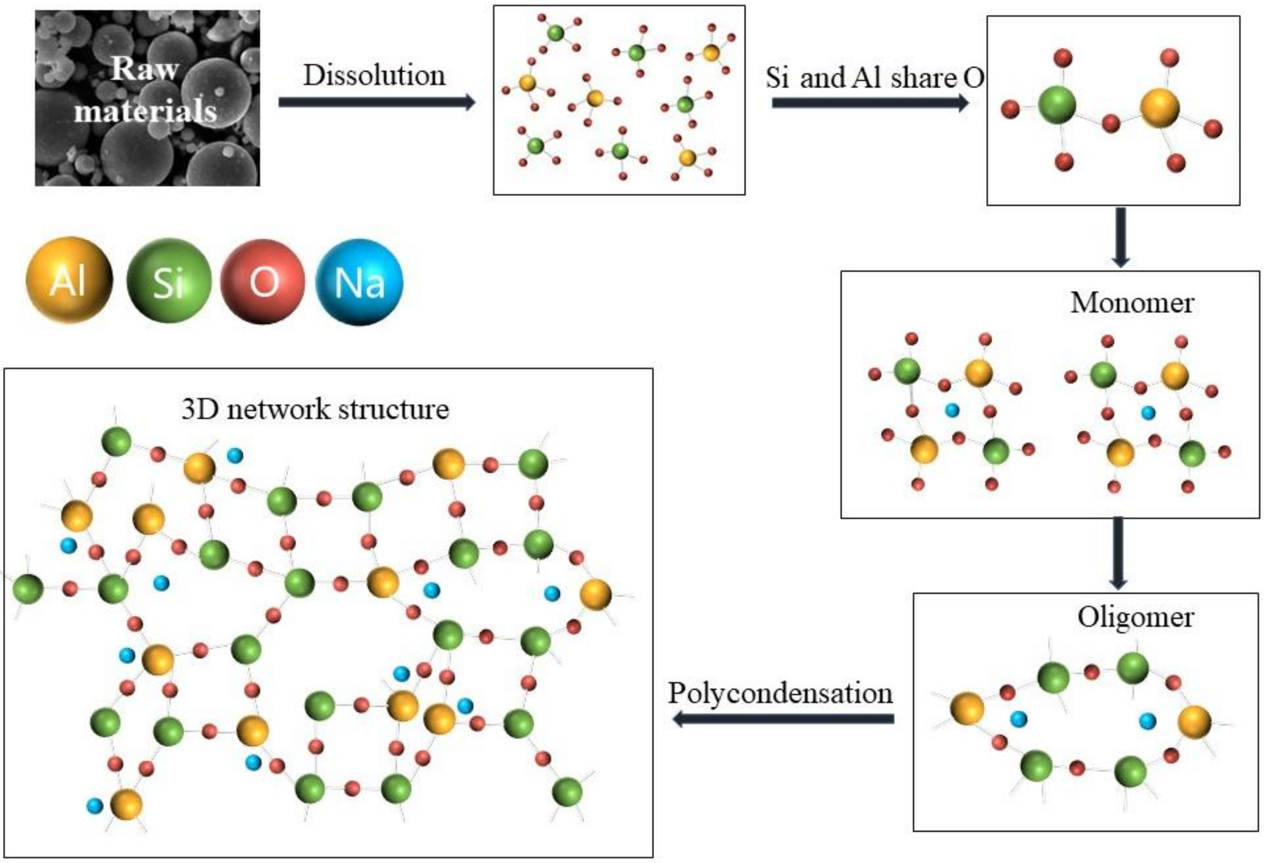


Figure 3: The geopolymerization chemical process [5]

Under the global backdrop of advocating energy conservation and emission reduction, EGC has gradually emerged as a new research focus. Tensile performance, as a crucial mechanical property index of concrete materials, is a significant parameter for the application of EGC in the field of engineering construction.

3. The Factors Influencing the Tensile Properties of EGC

3.1 The type of Precursor

Among various aluminosilicate materials, fly ash and ground granulated blast-furnace slag (GGBFS) are the most frequently employed precursors in EGC. Fly ash is the precursor most utilized in EGC research because, as a by-product of coal-fired power plants, it is widely accessible worldwide [1]. However, fly ash-based geopolymer concrete requires high-temperature curing to attain ideal performance. The high calcium oxide content in GGBFS can enhance the reactivity of the composite material and increase the early strength gain. Therefore, GGBFS has been employed to partially or completely substitute for fly ash in EGC.

It can be observed from Figure 4 that the research results of Verma et al. [6] demonstrate that when the proportion of slag ranges from 0 to 75%, the tensile strength of EGC gradually increases with the increase of the proportion of slag in the precursor. At 28 days, compared with the fly ash-based specimens, the tensile strengths of the specimens containing 25%, 50%, and 75% slag were 14.3%, 33.3%, and 47.6% higher than that of the fly ash-based EGC, respectively. Ling et al. [7] discovered that within the range of 0 - 30%, replacing fly ash with slag can enhance the tensile strength of EGC, with the maximum increase achieved when the slag proportion was 20%, increasing by 44.7%. The research of Feng et al. [8] also arrived at similar conclusions, where the tensile strength of EGC was the greatest when the slag proportion was 20%. Lao et al. [9] compared the substitution effects with slag replacement rates of 20%, 50%, and 80% respectively and found that the tensile strength of EGC was the lowest when the slag replacement rate was 50% and the highest when it was 80%. Alrefaci et al. [10] compared the tensile strengths of EGC containing 50% and 100% slag and found that the tensile strength of EGC with 100% slag as the precursor was higher than that of EGC with a mixture of 50% slag and 50% fly ash.

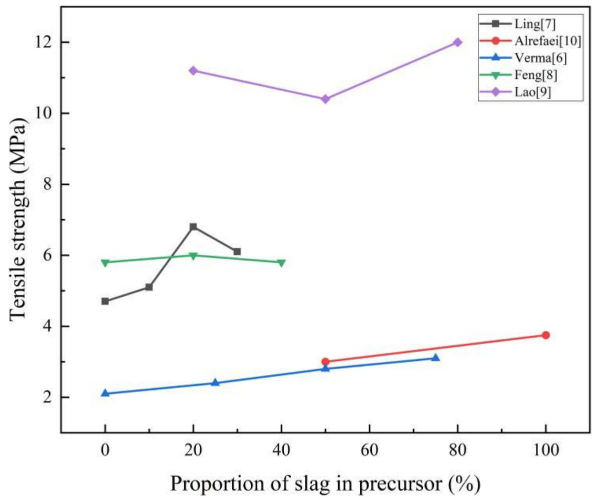


Figure 4: The effect of slag proportion on the tensile strength of EGC

3.2 Alkaline Activator

The type of alkaline activator can exert a significant influence on the tensile performance of geopolymers. Commonly utilized activators for alkali activation include sodium-based and potassium-based ones. Generally, EGC activated by sodium-based activators typically exhibits superior tensile performance compared to that activated by potassium-based activators. The degree of geopolymerization of the sodium-based EGC matrix is higher, featuring higher density and lower porosity, which enhances the mechanical properties of EGC. Hence, compared to other types of activators, EGC prepared with sodium-based activators demonstrates better performance [11]. Moreover, studies have revealed that sodium-based activators composed of sodium hydroxide and water glass solution yield more desirable mechanical properties than those prepared using sodium hydroxide solution alone [12].

The tensile performance of EGC is not only influenced by the type of alkaline activator but also by its chemical composition. The molarity of the alkali-activated solution can impact the polymerization degree of the geopolymer, thereby influencing the formed aluminosilicate gel and ultimately the tensile performance of EGC [13]. The effect of the molarity of NaOH on the tensile strength of EGC is depicted in Figure 5. The research findings of Cai [14] and Han et al. [15] indicate that within the range of 6 - 14 mol/L, the tensile strength of EGC increases with the rise of the molarity of NaOH, with the maximum increase in tensile strength reaching up to 335%. Pan et al. [16] also obtained a similar conclusion, but the tensile strength of EGC declined at a molarity of 12 mol/L, yet it remained higher than the results at 6 and 8 mol/L. Excessively high concentrations might deteriorate the tensile performance of EGC. The studies by Khalaj et al. [17] and Zahid et al. [18] discovered that when the NaOH molarity reached 16 mol/L, the tensile strength decreased. Furthermore, some research indicates that the influence of the molarity of NaOH on the tensile strain capacity of EGC differs from that on the tensile strength. The lower the molarity of NaOH, the stronger the tensile strain capacity of EGC.

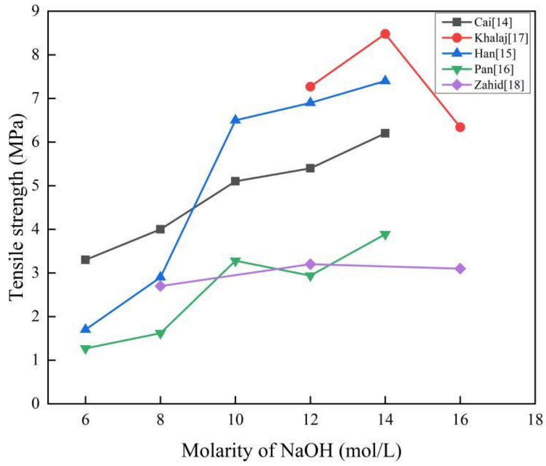
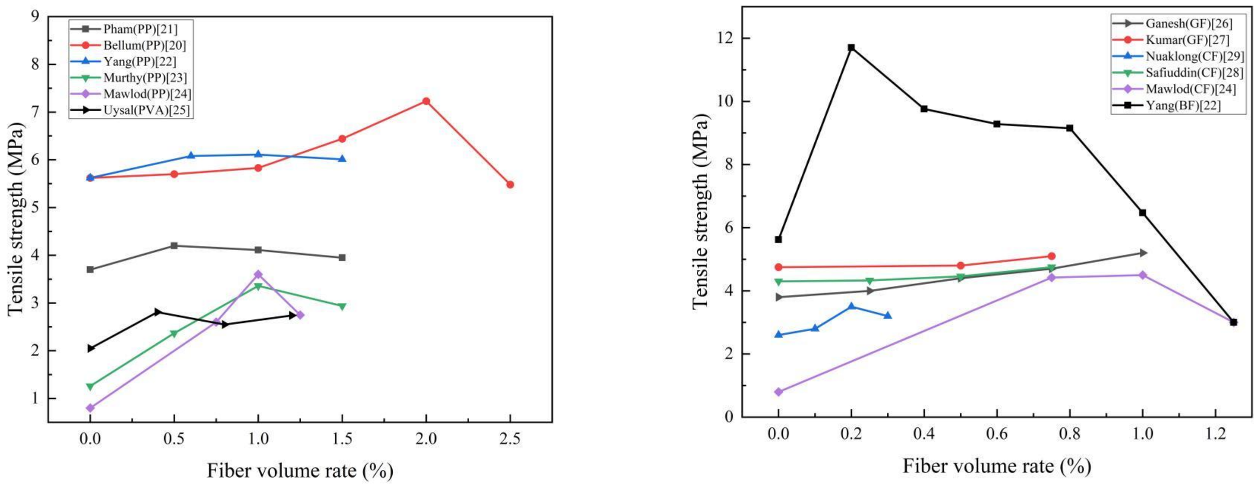


Figure 5: The effect of NaOH molarity on the tensile strength of EGC

3.3 Fiber Type and Volume Rate

Existing relevant studies indicate that when fibers are added as reinforcing materials to the matrix of geopolymers, fibers can enhance the tensile strength and tensile strain capacity of EGC, thereby ameliorating the brittleness of EGC [19].

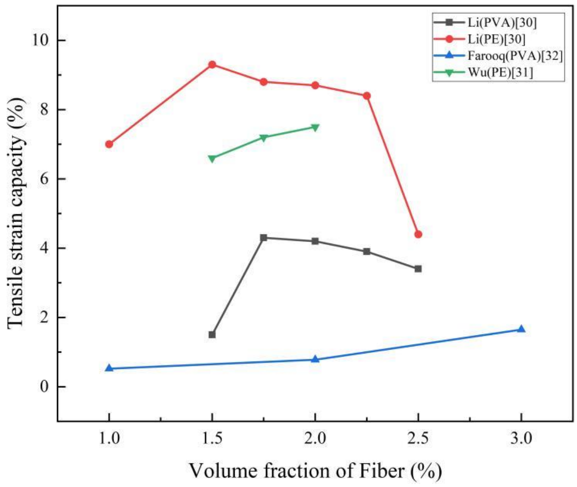


(a) Synthetic fiber (b) Inorganic fiber

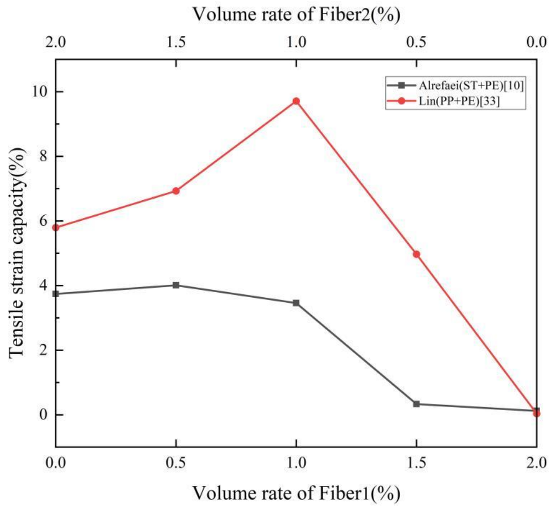
Figure 6: The effect of fiber volume rate on the tensile strength of EGC

Figure 6 presents the effects of the volume rates of synthetic fibers and inorganic fibers on the tensile strength of EGC. Figure 6(a) reveals that, in general, the incorporation of polypropylene (PP) fibers and PVA fibers can enhance the tensile strength of EGC. The research results of Bellum et al. [20] suggest that within the range of 0 - 2%, the tensile strength of EGC strengthens with the increase of the PP fiber content, with the maximum strength increase reaching 28.65%. However, when the PP fiber content increases to 2.5%, the tensile strength of EGC decreases by 2.49%. Pham et al. [21]–[22] discovered that within the range of 0-1.5%, the addition of PP fibers leads to varying degrees of improvement in the tensile strength of EGC. In the experiments of Murthy et al. [23], the addition of 1% PP fibers increased the tensile strength by 167%. Mawlod et al. [24] also obtained a similar conclusion, with the maximum tensile strength achieved when the PP fiber content was 1%, increasing by 350%. Uysal et al. [25] found that PVA fibers can increase the tensile strength of EGC, with the maximum increase at a PVA fiber volume rate of 0.4%, which was 36.86%. Figure 6(b) analyzes the impact of the volume rate of inorganic fibers on the tensile strength of EGC. Ganesh et al. [26]–[27] discovered that within the range of 0 - 1%, the increase in the volume rate of glass fibers (GF) has little influence on the tensile strength of EGC. When the GF content is 1%, the increase in the tensile strength of EGC reaches the maximum, which is 37%. The research results of

Safiuddin et al. [28] and Nuaklong et al. [29] indicate that carbon fibers (CF) have a relatively small effect on the tensile strength of EGC, with the maximum increase rates of the tensile strength being 10% and 35% respectively. Mawlod et al. [24] found that when 0.75% and 1% CF were added, the tensile strength of EGC was significantly enhanced. The research results of Yang et al. [22] show that within the range of 0-1%, the tensile strength of EGC first increases and then decreases with the increase in the volume rate of basalt fibers (BF), reaching the maximum at 0.2%, with an increase rate of 108%.



(a) Single fiber



(b) Hybrid fiber

Figure 7: The effect of fiber volume rate on the tensile strain capacity of EGC

Figure 7 summarizes and analyzes the effects of the common fiber volume rates on the tensile strain capacity of EGC. Figure 7(a) represents the effect of incorporating a single type of fiber into EGC on the tensile strain capacity. The experimental study by Li et al. [30], where PVA and PE fibers were incorporated respectively, indicated that the tensile strain capacity reached the maximum when the volume rate of PE fibers was 1.5%, and then decreased with the increase of the fiber volume rate. The addition of 2.5% PE fibers led to a reduction of 52.7% compared to 1.5%. The incorporation of PVA fibers presented a similar trend, with the tensile strain capacity reaching the maximum when the incorporated volume was 1.75%, and then decreased with the increase of the fiber volume rate. Wu et al. [31] discovered that within the range of 1.5 - 2%, the tensile strain capacity enhanced with the increase of the PE fiber volume rate. Farooq et al. [32] incorporated 1%, 2%, and 3% volume rates of PVA fibers into EGC respectively. The research results found that the tensile strain capacity was the strongest when a 3% volume rate of PVA fibers was added, which increased by 50% and 217% respectively compared to the addition of 1% and 2%. Overall, the enhancement effect of PE fibers on the tensile strain capacity of EGC is superior to that of PVA fibers.

The effect of the volume rate of hybrid fibers on the tensile strain capacity of EGC is depicted in Figure 7(b). The research findings of Alrefaei et al. [10] revealed that when 1.5% PE fibers and 0.5% SF were hybridized and added to EGC, its tensile strain capacity was greater than that of EGC with only 2% PE fibers. Once the content of SF exceeded 0.5%, the tensile strain capacity of EGC began to decline. Lin et al. [33] investigated the hybrid effect of PE and PP fibers and discovered that when 1% PE fiber and 1% PP fiber were incorporated, the tensile strain capacity of EGC reached the highest level of 9.711%. Moreover, the study found that if 2% of PE, PP, and SF fibers were added individually, the enhancement effect of PE fibers on the tensile strain capacity of EGC was superior to that of SF and PP fibers.

4. Conclusion

Based on the research data from relevant literature, this paper mainly conducts statistical processing and analysis on the influencing factors of the tensile properties of EGC. The main conclusions are as follows:

(1) Fly ash and GGBFS are the prevalent precursor materials for EGC. Moderately substituting fly ash in the precursor with GGBFS can enhance the tensile strength of EGC.

(2) The type of alkaline activator and its molarity have a remarkable influence on the tensile performance of EGC. An increase in the molar concentration of NaOH within a certain range can strengthen the tensile strength of EGC.

(3) The tensile properties of EGC is correlated with the type, volume rate and hybridization of fibers. Different EGCs have different optimal fiber volume rates. Compared with PP fibers and SF, PE fibers have a superior effect on improving the tensile strain capacity of EGC. The effect of fiber hybridization on the tensile strain of EGC is significantly influenced by the ratio of the two fibers.

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