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Fiber-Reinforced Geopolymer Concrete: A Comprehensive Review of Mechanical Performance and Durability

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Abstract: Geopolymer concrete (GPC) is now a promising, green choice over traditional OPC concrete, helping cut down on carbon emissions and using up industrial by-products. Still, regular GPC struggles with being too brittle and having low tensile strength and high drying shrinkage, limiting how much you can build with it. To fix these issues, adding different micro- and macro-fibers has become a major focus in research.

To beat these problems, adding different kinds of micro- and macro-fibers is a hot spot in research right now. This paper sums up the latest progress in Fiber-Reinforced Geopolymer Concrete (FRGPC). It looks at how various types of fibers – including steel, synthetic like PVA and polypropylene, carbon, and even natural fibers – affect the fresh properties, mechanical strength, and long-term durability of GPC.

Fiber inclusion often makes the mixture less workable but it greatly boosts tensile strength, flexibility in bending, energy absorption ability, and resistance to cracking. The paper checks how FRGPC performs in nasty conditions like acids, sulfates, freeze-thaw cycles, and extreme heat. It also uses SEM, XRD, and FTIR to look at fiber-matrix interactions and the intertransition zone.

It points out some research gaps and real-world problems too, hoping to get FRGPC ready for wide use in green building projects.

Keywords: Fiber-reinforced geopolymer concrete, Mechanical performance, Durability properties, Microstructural analysis, Flexural toughness, Sustainability

I. Introduction

The construction industry is wrestling with a huge sustainability issue due to its big use of Ordinary Portland Cement (OPC). Making OPC eats up tons of energy and pumps out about 8% of the world's man-made CO2, on top of guzzling up lots of raw materials [1]. To fight this eco-nightmare, people have turned to geopolymer concrete (GPC), a green rival to regular cements. Instead of OPC, GPC uses industrial leftovers like fly ash, GGBS, and metakaolin, which get jazzed up in an alkaline bath, forming aluminosilicate goo [2]. Not only does this cut carbon emissions by around 80%, it also fits perfectly into a circular economy, transforming factory trash into primo building goods.

While GPC boasts high compressive strength and thermal stability, it's pretty brittle on its own. It doesn’t do well under tension or bending since it picks up lots of tiny cracks that get worse with time, making it perform poorly in more dynamic situations [3]. Adding short discrete fibers transforms it into fiber-reinforced geopolymer concrete (FRGPC). These fibers, whether micro or macro (like steel, PVA, PP, and even sustainable natural fibers), help by bridging cracks. They move the concrete from failing suddenly to bending more before breaking [4], [5].

There are plenty of studies looking at different aspects of geopolymer composites. However, there isn't a one-stop resource explaining how various fiber setups influence fresh concrete behavior, its strength, and durability in harsh conditions across different geopolymer mixes. That's why this review aims to bring together all the latest FRGPC research. It looks at how fiber types and amounts affect the concrete's performance and longevity. It connects big mechanical changes to what's happening on a tiny scale within the material, spots the areas where we need more research, and sets out paths for future development, including standards for this green concrete.

II. Raw Materials and Geopolymerization

2.1 Source Materials

The synthesis of geopolymer concrete (GPC) relies on industrial by-products or natural materials that have a lot of amorphous silica (SiO_2) and alumina (Al_2O_3). One of the most studied materials is low-calcium class F fly ash (FA), which comes from coal-fired power plants. It's prized because of its spherical shape, which makes the mixture more workable when you first create it, sort of like how ball bearings make things roll smoother [6]. On the other hand, ground granulated blast-furnace slag (GGBS), a by-product of iron manufacturing with a lot of calcium, is used to help the curing happen at regular temperatures. But be careful, the calcium in GGBS leads to the formation of a calcium-alumino-silicate-hydrate (C-A-S-H) gel, along with the usual sodium-alumino-silicate-hydrate (N-A-S-H) geopolymer framework [7]. Then there's metakaolin (MK), made by heating kaolinitic clay. It's very reactive but it needs a lot of water and you often have to add more superplasticizer to deal with that [8].

2.2 Alkaline Activators

For geopolymerization, you need a strong alkaline solution to break down the aluminosilicate precursors into reactive pieces. Usually, a mix of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) works best [9]. The strength of the NaOH, measured in moles (generally between 8M and 16M), affects how quickly Si^{4+} and Al^{3+} ions dissolve, giving you a denser matrix if the concentration is stronger. Yet, if it's too intense, you could get quick setting—definitely something to watch out for [10]. The ratio of Na_2SiO_3 to NaOH (usually kept between 1.5 and 2.5) determines the Si/Al ratio, and that really shapes the final strength of your structure [11].

2.3 Classification of Fibers

In geopolymer concrete, GPC for short, fibers get sorted based on what they're made from:

- Steel fibers come in different shapes like hooked-end, crimped, or straight. These guys add lots of tensile strength and stiffness, making them great for stopping big cracks during peak loading [12].
- Synthetic fibers do cool stuff too. PVA fibers bond really well with the GPC thanks to hydroxyl groups on their chains. This means they provide slip-hardening behavior [13]. On the other hand, PP fibers have a lower stiffness and mainly help prevent early shrinkage and boost fire resistance [14]. Carbon and basalt fibers can handle high temps and carry tons of tension, yet they're pricey [15].
- Natural fibers: Plant-derived fibers such as sisal, coir, jute, and bamboo represent ultra-low-carbon reinforcement options. However, their hydrophilic nature and vulnerability to degradation in highly alkaline geopolymer pore solutions require specialized chemical pre-treatments, like with alkalization [16].

III. Fresh Properties

The rheological behavior of fiber-reinforced geopolymer concrete (FRGPC) differs a lot from what we see in unreinforced systems. Adding fibers ups the internal friction in the fresh mix, which drops the slump and workability [17]. This change depends a lot on the fiber aspect ratio (l/d) and volume fraction (V_f). When you use high aspect ratio fibers or go above 1.5% volume fraction, it can cause serious issues like fiber interlocking, leading to segregation and balling during mixing [18]. Plus, synthetic fibers such as PVA, thanks to their large surface area-to-volume ratio, soak up more water and activators than hydrophobic steel fibers do, cutting down on the free liquid that helps in lubrication [19]. As a result, using naphthalene or polycarboxylate-based superplasticizers is crucial, alongside optimized aggregate grading, to make sure the compaction is good but not at the cost of speeding up the setting time [20].

IV. Mechanical Performance

4.1 Compressive Strength

The way fiber reinforcement influences the compressive strength of GPC is a bit complicated. With optimal fiber volumes, like 0.5% to 1.0% for steel and 0.1% to 0.3% for PP, they add a lateral confining effect that holds back micro-crack coalescence and slightly bumps up the strength [21]. However, add too many fibers and you introduce lots of air voids and make compaction tricky. That leaves you with a weaker porous microstructure that saps away strength [22].

Various studies have indicated that exceeding the optimal threshold of fibers can induce structural porosity, leading to a subsequent drop in compressive strength (**Table 1**)

Table 1: Summary of the effects of various fiber types and volume fractions on the mechanical properties of geopolymer concrete.

Binder Type	Fiber Type & Geometry	Volume Fraction (Vf)	Key Mechanical Findings	Ref.
Fly Ash (Class F)	Steel (Hooked-end)	0.5% - 1.5%	Flexural strength increased up to 45%; altered failure mode from brittle to ductile.	[12, 21]
Fly Ash + GGBS	PVA (Straight)	0.1% - 0.3%	Significant deflection-hardening behavior and high fracture toughness observed.	[13, 24]
GGBS	Polypropylene (PP)	0.1% - 0.5%	Slight reduction in compressive strength at >0.3%; minor increase in splitting tensile.	[14, 22]
Metakaolin	Carbon / Basalt	0.5% - 1.0%	High initial cracking load; dramatic improvement in energy absorption capacity.	[15, 16]

4.2 Tensile and Flexural Strength

When it comes to tensile and flexural strength, FRGPC excels. Unreinforced GPC splits easily under load because it lacks fiber reinforcement. Steel fibers stop advancing cracks and take a good amount of pullout stress, deforming and soaking up a lot of energy in the process, which leads to a ductile and multi-cracking failure mode [24]. Meanwhile, PVA fibers, through controlled interfacial debonding, manage to get high flexural toughness and deflection-hardening [25].

4.3 Bond Strength and Interfacial Mechanics

The fibers work is all about the interface between them and the matrix. Since geopolymer binders don't have the buildup of weak calcium hydroxide crystals around aggregates and fibers like in OPC, the interfacial transition zone (ITZ) ends up denser and more uniform [26]. Even better, a small amount of fiber surface etching due to the alkaline activator improves mechanical interlocking, although pushing it too far could start eating away at synthetic and natural fibers [27].

V. Durability Properties

5.1 Shrinkage Actions

Let's touch on durability properties. Drying shrinkage hits high-GGBS-content GPC pretty hard because a bunch of structurally uncombined water evaporates from the pores in N-A-S-H or C-A-S-H gels. But if you add some short synthetic fibers, like PP or nylon, you limit those troubles. These fibers stop the growth of tensile stresses that pop up during drying and help control overall volume change and the birth of tiny cracks [29].

The melting of polypropylene fibers at elevated temperatures creates interconnected channels that relieve internal steam pressure, thereby eliminating explosive spalling (**Table 2**).

Table 2: Durability performance and degradation mechanisms of fiber-reinforced geopolymer composites under aggressive environmental regimes.

Durability Regime	Dominant Fiber Type	Matrix Impact & Mechanism	Key Outcomes	Ref.
Drying Shrinkage	PP and Nylon fibers	Fibers intercept internal tensile stresses caused by capillary pressure.	Micro-crack propagation restricted; macro-volumetric changes reduced.	[28, 29]
Acid Attack (H_2SO_4)	Carbon and Steel	Geopolymer cross-linked matrix resists gypsum formation; fibers maintain core integrity.	Prevented catastrophic structural splitting even after partial matrix neutralization.	[30, 31]
Elevated Temp. (>400°C)	Polypropylene (PP)	PP fibers melt at ~165°C, creating interconnected micro-channels.	Internal steam pressure released safely; eliminated explosive spalling.	[32, 33]

5.2 Chemical and Acid Attack

What really stands out with GPC is how stable it is in harsh acidic and sulfate settings. Unlike OPC, which balloons when hit with sulfuric acid due to gypsum and ettringite, GPC slowly loses framework ions (Al^{3+}) without dramatic expansions [30]. By tossing in acid-resistant fibers like carbon, basalt, or premium steel, the composite keeps its ability to carry loads despite matrix neutralization [31].

5.3 High-Temperature and Fire Exposure

When you expose GPC to high temps (above 400°C), it might spall if there's moisture caught in the pores. As that steam builds, it can rip apart the matrix. But throwing in PP fibers, which melt around 160°C to 170°C, saves the day. The melt opens gaps to vent off the pressure safely and shields the core [33].

VI. Microstructural Analysis

Probing deeper with tech like Scanning Electron Microscopy (SEM), it's usually clear that steel and PVA fibers in geopolymer pastes sit in highly continuous ITZ with no real fractures [34]. More studies verify that the interfacial shearing takes the brunt of the energy, not any sudden tearing of the fibers. Also, with X-ray Diffraction (XRD) and Fourier-Transform Infrared Spectroscopy (FTIR), the unchanged pattern in silicon-oxygen stretching proves that the basic dynamics of geopolymerization remain untouched with the simple addition of inert fibers [35].

Fractography analysis confirms that energy dissipation during failure is governed by interfacial sliding and fiber pull-out rather than sudden fiber rupture (**Table 3**)

Table 3: Microstructural characterization and interfacial transition zone (ITZ) phenomena in fiber-reinforced geopolymer matrices.

Microstructural Technique	Focus Area	Observed Phenomenon & Features	Structural Significance	Ref.
SEM (Scanning Electron Microscopy)	Fiber-Matrix ITZ	Highly continuous transition zone; presence of distinct fiber pull-out grooves.	Confirms failure occurs via energy-dissipating interfacial sliding rather than sudden rupture.	[26, 34]
FTIR (Fourier-Transform Infrared)	Geopolymer Network	Asymmetric stretching vibrations of Si-O-T bonds remain stable at 1000cm^{-1}.	Proves that the inclusion of inert fibers does not hinder or disrupt geopolymerization kinetics.	[35]
XRD (X-ray Diffraction)	Crystalline Phases	Co-existence of amorphous halo with sharp quartz and calcite peaks.	Identifies simultaneous formation of N-A-S-H and C-A-S-H gels in blended systems.	[7, 27]

VII. Challenges and Future Perspectives

Geopolymer-reinforced green cementitious composites offer great benefits both structurally and environmentally, but several hurdles slow down their widespread use. First off, there's no standard global design code or testing spec for these composites, meaning engineers often must work with tweaked Portland cement codes instead [3]. Another big issue, Using chemical activators creates safety hazards for workers at ready-mix plants. To move things forward, we need to develop easier “just-add-water” mixes using solid activators. Plus, we should run studies on how well these composites hold up in the field under actual conditions to prove that lab results are accurate.

VIII. conclusion

This review emphasizes that including both micro and macro fibers into geopolymer concrete significantly reduces its brittleness and susceptibility to shrinkage. Even though these fibers can decrease workability because of the extra friction, they totally change how the material fails mechanically. Instead of cracking catastrophically, the geopolymers get this more controlled, kind of bendy behavior. Specifically, steel and PVA fibers are really good at stopping cracks from spreading. They boost the material’s flexibility, strength, and its ability to soak up energy when stressed. On top of that, fiber-reinforced geopolymer concrete fares much better in harsh environments like acid baths or hot spots thanks to fibers that prevent explosive cracking. These volatile fibers create teeny channels for steam to escape during high heats.
To back up these big effects, researchers used tools like SEM, XRD, and FTIR. This tech confirms that the tough stuff is working on a microscopic level too—creating better fiber-matrix bonding that doesn’t slow down the geopolymer’s natural forming process. However, before this becomes common in real-world projects, we need to iron out some kinks regarding safety, testing, and making global design standards. Getting past these hurdles should help bring this super sustainable concrete from lab experiments to the construction site.

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