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ANALYSIS OF RESEARCH TRENDS ON SELF-COMPACTING GEOPOLYMER CONCRETE WITH FIBERS

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Abstract

The environmental impact of Portland cement production, particularly its high carbon emissions, has raised significant concerns in the construction sector. Geopolymer concrete offers a more sustainable alternative, but research on self-compacting geopolymer concrete (SCGC) reinforced with fibers remains limited compared to SCGC without fibers. To fill this gap, this study conducted an in-depth literature review using the Publish or Perish application with Scopus data and VOS-viewer software for bibliometric analysis. The resulting bibliometric map reveals the network of keyword connections, shedding light on emerging trends and key focus areas in SCGC research. This review not only explores the fresh and mechanical properties of SCGC with fiber variations but also provides insights that can direct future studies in this field. The aim is to encourage further research and innovation, contributing to the development of more efficient and sustainable SCGC with fiber reinforcement in construction practices.

Keywords: bibliometric analysis, self-compacting geopolymer concrete, fibers, mechanical properties, fresh properties

1. INTRODUCTION

Concrete is one of the most widely used construction materials globally, composed of a mixture of water, cement, sand (fine aggregates), gravel (coarse aggregates), and various additives to enhance its quality. However, the main component of concrete, cement, is a major source of greenhouse gas emissions, particularly carbon dioxide (CO_2). The production of cement involves heating limestone to extremely high temperatures-a process that releases large amounts of CO_2. Estimates indicate that the cement industry contributes approximately 5% to 8% of all human-caused CO_2 emissions worldwide[1,2]. This reality has raised significant concerns about the environmental impact of cement production, prompting

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efforts to identify more sustainable alternatives and reduce emissions [3]. The European Union (EU) has recognized the pressing need for the cement industry to substantially reduce its carbon footprint, reflecting its commitment to addressing climate change [4]. Various strategies have emerged in response to this challenge, including the development of alternative materials and technologies aimed at decreasing cement consumption during concrete production. Notably, geopolymer concrete has garnered attention as an innovative alternative to traditional concrete. Geopolymer concrete primarily consists of silica and aluminum, which are abundant in industrial waste, particularly fly ash produced by coal-fired power plants [5,6]. This type of concrete not only utilizes waste materials, which contributes to resource conservation, but also significantly reduces greenhouse gas emissions associated with cement production [6].

Research indicates that geopolymer concrete can lead to a notable decrease in the environmental impacts when compared to conventional concrete made with ordinary Portland cement. Geopolymer concrete is known for its excellent resistance to fire, sulfate attacks, and has relatively low creep and shrinkage properties [7]. However, one of its significant drawbacks is its low ductility and poor crack resistance, which limits its ability to withstand tensile forces compared to traditional concrete. Studies have shown that while geopolymer concrete may exhibit similar compressive strength to conventional concrete, its brittle behavior is more pronounced. Some research suggests that incorporating fibers into the mix can improve these mechanical properties by enhancing the concrete's toughness. Nevertheless, the addition of fibers often results in a reduction in workability, making it harder to mix and place the concrete effectively [8].

In construction, especially when using conventional or geopolymer concrete, vibrators are commonly used to ensure proper compaction. However, when there is dense reinforcement, achieving the desired level of compaction becomes challenging, leading to problems such as segregation. Self-compacting concrete (SCC) and Self-compacting geopolymer concrete (SCGC) offer a promising solution to this issue. These innovative materials are designed to flow smoothly into all parts of the formwork, eliminating the need for external vibration. The advantages of SCC and SCGC include their ability to reach confined spaces, provide excellent compaction without segregation, improve the bond strength between aggregates and binder materials, and accelerate construction processes. Additionally, these materials help reduce overall costs, making them particularly suitable for projects with complex geometries or heavy reinforcement [9].

Bibliometric analysis using VOS-viewer can provide valuable data on research trends and themes in various fields. VOS-viewer software is commonly used for bibliometric analysis to identify research opportunities and popular references in a particular field. By utilizing VOS-viewer, researchers can visualize the distribution of research topics and research trends. These visualizations can help researchers identify gaps in the current literature, track changes in key research areas, and find potential collaborators for future research. In addition, VOS-viewer can help in determining the impact of a particular research topic, highlighting the most influential studies and authors. Overall, the use of VOS-viewer in bibliometric analysis of research can provide valuable insights for academics and professionals who want to stay informed about the latest advances and trends in the field [10].

Bibliometric analysis is a method used to evaluate the influence and reach of scientific publications by examining citation data. It assesses both the quantity and quality of research outputs through various metrics, including the number of publications, citations, collaborations, and their overall impact [11]. By conducting bibliometric analysis, researchers can uncover emerging trends, patterns of collaboration, scientific networks, and identify gaps in knowledge, particularly in areas like self-compacting geopolymer concrete (SCGC) with fibers. The aim of this study is to explore the trends, gaps, and potential research opportunities in the field of SCGC reinforced with fibers. SCGC with fibers is increasingly being developed because fibers can enhance tensile strength, crack resistance, and the long-term durability of concrete. Additionally, SCGC itself is a more environmentally friendly alternative to conventional concrete. This paper helps researchers track the latest advancements in the use of various types of fibers, understand how fibers influence mechanical and fresh properties, and align research trends with real-world construction needs and sustainability goals.

2. METHODOLOGY

This study uses a bibliometric analysis method. In this study, data collection used the Harzing's Publish or Perish application, accessed on February 4, 2024 with a time span of 2010-2024, the keyword "fiber self-compacting concrete with geopolymer concrete" search, the database used is an international journal indexed in Scopus, there are only 19 publication data. Because there are only a few publications, another data search was carried out with the keywords "self-compacting geopolymer concrete" and the keyword "geopolymer concrete with fibers" there are 200 publication data each. The data search results can be seen in Table 1. Then the data was analyzed using VOS-viewer to obtain visual data mapping to determine the research trend of self-compacting geopolymer concrete with fibers.

Table 1. Article screening results

Data Matrix	Initial Search	Refinement Search	Refinement Search
Keyword	fiber self-compacting concrete with geopolymer concrete	geopolymer concrete with fibers	self-compacting geopolymer concrete
Source	Scopus	Scopus	Scopus
Articel	19	200	200
Citation	280	6492	2982
Cites peryear	25.45	649.20	271.09
Cites perauthor	280.00	6492.00	2982.00
Author per articel	14.74	32.46	14.91

3. RESULT AND DISCUSSION

The Publish or Perish application is an invaluable tool for researchers in assessing the impact of their scholarly work. By utilizing metrics such as citation count and h-index, this tool helps identify emerging research trends, enabling academics to contribute more strategically to scientific advancements [12,13]. Based on Table 2, several highly cited studies stand out. One of them is [14], which focuses on self-compacting geopolymer concrete (SCGC) reinforced with fibers, accumulating 211 citations. This high citation count reflects the growing academic interest in SCGC as a sustainable alternative in concrete technology [15]. Other notable studies by [16] and [17], with 182 and 166 citations, respectively, highlight the durability and mechanical performance improvements in fiber-reinforced geopolymer concrete using steel and polypropylene fibers.

Beyond geopolymer concrete, the use of natural and synthetic fibers in construction is also gaining attention. [18] found that basalt fibers enhance the durability and strength of fiber-reinforced concrete, while [19] demonstrated that jute and sisal fibers contribute to improved tensile and compressive strength while reducing environmental impact. Interestingly, several studies have emphasized the benefits of combining natural and synthetic fibers in concrete. [20] and [21] discovered that natural fibers, such as banana fibers, could serve as an eco-friendly alternative in construction materials. Meanwhile, [22] highlighted how the type and arrangement of carbon fibers significantly affect the mechanical performance of concrete. With advancements in material technology, the use of fiber-based hybrid composites is gaining interest for enhancing concrete strength and sustainability. Research by

[23] and [24] underscores the importance of fiber optimization and processing techniques to improve concrete performance under various conditions.

Table 2. Highly cited publications

Refs.	Articel	Types of Concrete	Types of Fibers	Citation
[14]	Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber	self-compacting geopolymer concrete	steel fiber	211
[16]	Durability characteristics of steel fibre reinforced geopolymer concrete	geopolymer	steel fiber	182
[17]	Flexural behavior of geopolymer composites reinforced with steel and polypropylene macro fibers	geopolymer	steel and polypropylene macro fibers	166
[25]	Mechanical and fracture properties of ultra-high performance geopolymer concrete: Effects of steel fiber and silica fume	ultra-high performance geopolymer	steel fiber	155
[26]	Assessing properties of alkali activated GGBS based self-compacting geopolymer concrete using nano-silica	self-compacting geopolymer concrete	-	152

VOS-viewer is a useful tool for analyzing and visualizing connections in bibliometric data, such as scientific publications, citations, and collaborations between researchers. It gathers data from various sources by searching for relevant keywords using Publish or Perish and then presents the results in an interactive network map. This map helps researchers see how different studies, keywords, and citations are interconnected.

Fig. 1 illustrates a network visualization generated with VOS-viewer, showing relationships between keywords in bibliometric data. In this visualization, nodes represent keywords, with larger nodes indicating more frequent occurrences in the dataset, while connecting lines (links) show how keywords are related. One interesting insight is the relatively small node for self-compacting geopolymer concrete (SCGC), which suggests that this research area is still in its early stages. This highlights a promising opportunity for researchers to explore SCGC further, as there is still plenty of room for new discoveries and developments. The small node size reinforces the idea that this field has not yet been fully explored, making it an exciting area for innovation and progress in sustainable concrete materials.

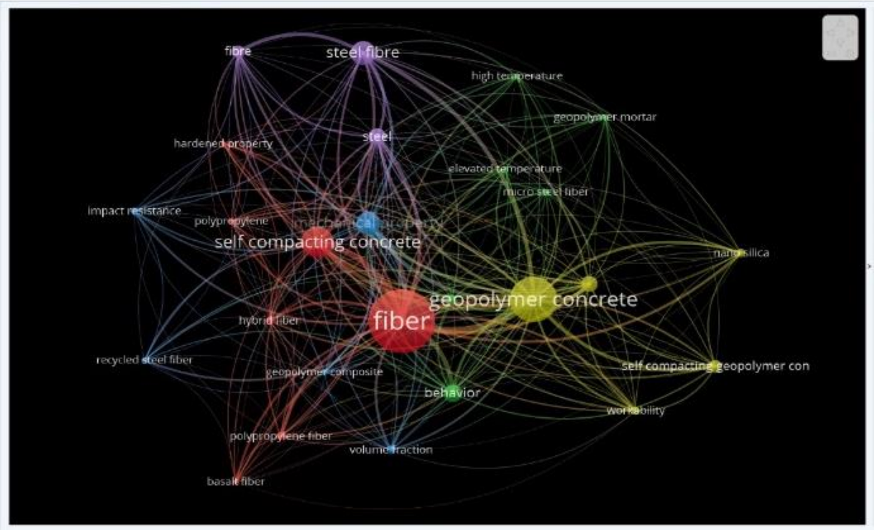

Fig.1. Network visualization

The Overlay Visualization feature in VOS-viewer helps track research trends over time by using color-coded nodes to represent publication years. Lighter colors, like yellow and green, indicate newer studies, while darker colors, like blue and purple, represent older research. A color legend provides a reference for understanding these time-based variations. In Fig. 2, the self-compacting geopolymer concrete (SCGC) node appears yellow, suggesting that this field is currently gaining interest and attracting more research attention.

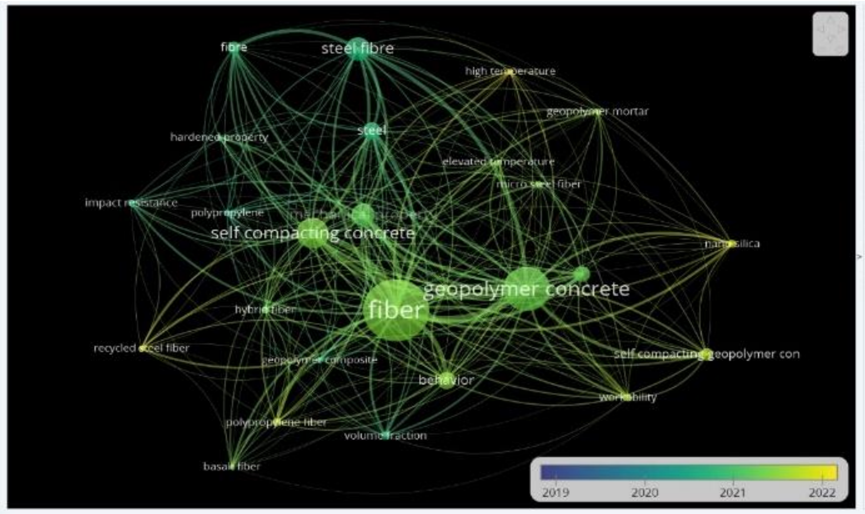

Fig. 2. Overay visualization

3.1. Constituents of SCGC

The mix design of self-compacting geopolymer concrete (SCGC) closely resembles that of traditional concrete, incorporating standard components such as binders, water, fine aggregates, and coarse aggregates. However, to meet the flowability requirements set by [27], the mix is supplemented with superplasticizers. While the composition follows the guidelines for self-compacting concrete (SCC), SCGC sets itself apart by utilizing geopolymer binders instead of conventional cement. These binders are derived from materials rich in silica and alumina, which are essential for the geopolymerization reaction. Alkaline activators such as sodium hydroxide or potassium hydroxide, combined with sodium silicate or potassium silicate, are commonly used to initiate the chemical process that forms the geopolymer structure [28].

The production of geopolymer concrete involves intricate chemical reactions, where even slight alterations in the process parameters can significantly affect the final properties of the material [29]. Fig. 3 depicts various factors that influence the workability and strength of SCGC. The diagram highlights key components such as the type and proportion of binder (for example, fly ash, slag, or metakaolin), coarse and fine aggregates, and the alkali activator that triggers the geopolymerization process. The mix ratio-especially the water-to-binder ratio and the use of superplasticizers-is crucial in determining how smoothly the concrete flows and its final strength. Additionally, uniform mixing and proper curing methods, along with external factors such as temperature, humidity, and setting time, also play a role in shaping the final properties of the concrete. The incorporation of fibers further contributes to enhancing both the strength and workability of the concrete. Overall, the interaction of these factors provides valuable insights for engineers and researchers in optimizing concrete formulations to meet specific construction needs. This study aims to synthesize existing research on the workability and mechanical properties of SCGC, particularly focusing on the role of fiber additions.

Fig. 3. Factor affecting workability and strength of SCGC [29]

A review of the literature reveals a notable gap in research on fiber-reinforced SCGC. To address this, Table 3 presents the mix proportions used in the creation of fiber-reinforced SCGC, while Table 4 highlights the types of fibers explored in the research. This compilation of data provides valuable insights into the potential benefits of fiber inclusion in SCGC, setting the stage for future studies aimed at optimizing the material's performance.

Table 3. List of publication reviews on mix proportions of SCGC with Fibers

SCGC Materials		[30]	[14]	[31]	[32]	[33]	[34]
Alkaline activator solution	Na_2SiO_3	202.5 kg/m^3	225 kg/m^3 (12M)	115 kg/m^3	130 kg/m^3	160.56 kg/m^3	165 kg/m^3
	NaOH	67.5 kg/m^3 (12M)		40 kg/m^3 (16M)	80 kg/m^3	64.34 kg/m^3 (12M)	75 kg/m^3
Binder	fly ash	360 kg/m^3	225 kg/m^3	300 kg/m^3	410 kg/m^3	-	-
	GBBS	90 kg/m^3	225 kg/m^3	200 kg/m^3	-	-	-
	metakaolin	-	-	-	-	500 kg/m^3	-
	wheat straw ash	-	-	-	-	-	475 kg/m^3
	nano silica	-	-	-	-	-	0%-3%
Fine Aggregate		1008 kg/m^3	865.61 kg/m^3	950 kg/m^3	760 kg/m^3	926.6 kg/m^3	680 kg/m^3
Coarse Aggregate		672 kg/m^3	742.88 kg/m^3	830 kg/m^3	960 kg/m^3	787.3 kg/m^3	1185 kg/m^3
Superplasticizer		10%	5%	2%	15 kg/m^3	8%	5.22 kg/m^3
Extra Water		10%	8%	24%	14 kg/m^3	24%	170 kg/m^3
Fiber		0%-1%	0%-1%	0-2%	0%-1.75%	0%-1.5%	0%-3.5%

According to Table 3, various studies on SCGC with fibers reveal a wide range of mix design strategies. Researchers adjust their formulations based on the specific objectives and technical requirements of their projects. For instance, while some studies combine fly ash with GBBS as the binder, others experiment with alternatives like metakaolin or wheat straw ash-and even include nano silica-to enhance the material's properties. This diversity is also seen in the use of alkaline activator solutions, where the quantities and concentrations of Na_2SiO_3 and NaOH are fine-tuned to achieve optimal reactivity. Additionally, the differences in the amounts of fibers, fine and coarse aggregates, superplasticizer, and additional water reflect ongoing efforts to strike the right balance between workability and mechanical strength. Overall, these varied material proportions underscore the innovative approaches used to develop SCGC that meets specific application needs.

Table 4. List of published reviews detailing the fibers types used by SCGC

Refs.	**Fiber Type**	**% of Fiber**	**Replacement**
[35]	steel fiber (hooked end), L=35mm, Ø=0.55mm, aspect ratio=65	0, 0.5, 1, 1.5% by volume fractions	fly ash, slag
[36]	polypropylene fiber, L=6 & 12 mm, Ø=31µm, aspect ratio= 193.55&387.09	0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8% by volume of geopolymer paste	fly ash, slag, silica fume
[32]	steel fiber (straight and brass-coated), L=13 mm, Ø=0.2mm	0, 0.25, 0.5, 0.75, 1, 1.25, 1.5%	fly ash
[31]	steel fibers (single hooked end), L=30mm, Ø=0.5mm, aspect ratio=60	0, 1, 1.5, 2 % of powder content	fly ash, ground granulated blast furnace slag
[34]	waste tire steel fiber, L=40mm Ø=0.9mm	0, 1, 1.5,2, 2.5, 3,3.5 % by binder content	wheat straw ash, nano silica
[14]	steel fibers (single hooked end), L=30mm, aspect ratio=40	0, 0.5, 1%	fly ash, nano silica

Refs.	Fiber Type	% of Fiber	Replacement
[30]	steel fiber (hooked end), L=35mm, Ø=0.5mm, aspect ratio =70	0, 0.5, 1 % by volume	fly ash, ground granulated blast furnace slag
[33]	steel fiber (straight and copper-coated), L=13mm, Ø=0.2mm	0, 0.5, 1, 1.5 by aggegate weight	metakaolin, fly ash, recycled aggregate, natural coarse aggregate
[37]			
[38]	steel fiber (hooked end, L=30mm	0, 1% by volume	fly ash, ground granulated blast furnace slag
[39]	micro-steel fibers, L=13mm, Ø=0.2mm, aspect ratio=65	0.5% by volume of the overall mixture	calcined kaolin clay, nano-lime

Based on Table 4, various studies on SCGC incorporating fibers reveal a diverse range of approaches in selecting fiber types. Researchers employ fibers with differing characteristics, from hooked steel fibers (whether straight or coated with copper or brass), to small-sized polypropylene fibers, and even steel fibers obtained from waste tires. Each fiber type is defined by specific parameters such as length, diameter, and aspect ratio that are optimized to enhance SCGC performance. Moreover, the proportions of fibers added vary-from as little as 0.25% up to 3.5%, whether measured by mix volume or aggregate weight. Additionally, some studies explore the use of alternative materials such as fly ash, slag, GGBS, silica fume, metakaolin, recycled aggregate, and nano-lime in the mix. This variety of approaches reflects the ongoing effort to optimize SCGC performance by tailoring the combination of fibers and other materials to meet specific application requirements.

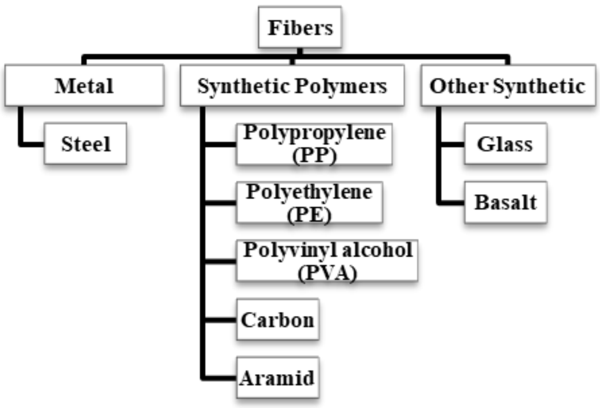

Fig. 4. Classification of common fibers [40]

The use of fibers as reinforcement in construction materials has gained significant attention in recent years, as growing evidence suggests that these additions-whether synthetic or natural-can enhance various material properties. Research categorizes fibers into two main types: synthetic and natural. As shown in Fig. 4, synthetic fibers, such as polyester, polypropylene, and glass fibers, are recognized for their high strength and consistent physical properties, making them a favorable choice for improving mechanical performance in construction applications [41,42]. Conversely, natural fibers-including hemp, kenaf, and bamboo-are increasingly utilized due to their biodegradability, cost-effectiveness, and abundant availability [43,21].

The integration of fibers into construction materials significantly enhances mechanical properties such as stiffness and deformation resistance while playing a crucial role in crack prevention [44,45]. In particular, the microstructural interaction between fibers and the matrix in geopolymer composite systems demonstrates that effective interphase bonding can improve mechanical performance and overall material durability [46,47]. However, research on fiber reinforcement in geopolymer composites remains in its early stages, emphasizing the need for further studies to unravel the complex interactions within the fiber-matrix system and their influence on material performance [48,49].

The increasing adoption of natural fibers in construction aligns with the global push for sustainability in the building materials industry. This transition not only provides an eco-friendly alternative but also supports economic viability in construction practices [42,50]. Studies indicate that natural fibers require approximately 17% less energy to manufacture compared to synthetic fibers, offering additional life cycle benefits [51]. The growing focus on the use of natural fibers in construction not only offers an eco-friendly and cost-effective alternative but also aligns with the global push for sustainability in the building materials industry [52]. Therefore, further research on fiber-matrix interactions is crucial to understanding the performance of these materials and their contribution to more sustainable and efficient construction practices.

Table 5. Chemical composition of varius binder in SCGC

Refs.	Binder	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
[14]	fly ash	1.60	62.33	21.14	7.15	2.40	0.10	3.37	0.38
	ground granulated blast furnace slag	34.12	36.40	11.39	1.69	10.30	0.49	3.63	0.35
	nano silica	-	99.80	-	-	-	-	-	-
[32]	fly ash	1.07	59.95	26.36	4.39	0.32	0.26	1.29	0.0
[35]	fly ash	26.80	31.90	15.90	14.10	3.70	2.50	2.00	2.00
	slag	39.00	32.30	15.40	0.60	7.20	1.20	0.40	0.70
[36]	fly ash	9.8	51.49		5.49	1.2	2.14	1.04	0.51
	silica fume	33.1	27.91	24.36	0.36	0.3	1.1	0.44	0.49
	slag	0.81	93.47	15.57	0.1	0.95	0.84	2.89	0.23
[37]	metakaolin	0.2	52.1	43.8	2.6	0.21	0	0.32	0.11
[30]	ground granulated blast furnace slag	32.4	36.3	21.7	1.08	5.89	0.48	-	-
	fly ash	2.1	57.78	25.78	9.5	1.3	0.63	0.72	0.33
[38]	fly ash	1.6	62.4	21.14	7.85	1.76	0.1	0.7	2.45
	ground granulated blast furnace slag	34.19	40.4	10.6	1.28	7.63	0.68	2.4	0.17

In geopolymer concrete, binder materials play a crucial role as the primary adhesive, similar to conventional concrete. These materials are rich in alumina and silica, which are essential for the geopolymerization process. Fly ash is the primary choice due to its availability and cost-effectiveness, while alternatives such as ground granulated blast furnace slag, metakaolin, silica fume, and agricultural waste ash (rice husk ash and wheat straw ash) are gaining attention for their potential to enhance concrete performance [53,54].

Table 5 presents the chemical compositions of various binders used in Self-compacting geopolymer concrete (SCGC), illustrating the flexibility in designing tailored concrete mixtures. The chemical composition of binders in SCGC varies, allowing for tailored concrete designs that meet specific functional and environmental needs. Fly ash is rich in silica, which supports geopolymerization, while ground granulated blast furnace slag, despite having lower silica content, still contributes to improved mechanical properties [55]. Studies show that the silica and aluminum oxide content in fly ash significantly influence the effectiveness of polymerization, while variations in alternative ash materials result in differing mechanical performance [56,57]. Other materials, such as metakaolin, which has high alumina content, have been proven to enhance concrete strength and durability. Silica fume also improves concrete resilience due to its high silica content. Beyond performance, utilizing industrial and agricultural waste as binder materials supports the circular economy and promotes sustainable construction practices [58,59].

3.2. The flow and workability properties of SCGC with the incorporation of fibers.

Geopolymer concrete typically exhibits high viscosity, which can lead to issues such as segregation or even structural damage if not properly compacted. To overcome this challenge, Self-compacting geopolymer concrete (SCGC) was developed. SCGC is an advanced type of concrete that eliminates the need for external compaction, as its inherent flowability and weight allow it to settle and compact naturally. The workability of SCGC is assessed through three critical factors: resistance to segregation, filling ability, and passing ability [29]. When selecting coarse aggregates for SCGC, it is important that their maximum size does not exceed 20 mm to ensure optimal flow characteristics. The experimental methods and permissible limits for these properties are specified in the [27] guidelines, as shown in Table 6.

Table 6. Acceptance limits for self-compacting concrete (SCC) are in accordance with [27] guidelines

Tests	Charecteristic	Class	Limits value	Units
Slump-Flow	Flowability	SF1	550-650	mm
		SF2	660-750	
		SF3	760-850	
T_{500}	Viscosity	VS1	≤ 2	sec
		VS2	> 2	
V-funnel	Viscosity	VF1	≤ 8	sec
		VF2	9 – 25	
L-Box	Passing ability	PA1	≥ 0.8	(h_2/h_1) with 2 rebars
		PA2	≥ 0.8	(h_2/h_1) with 3 rebars
Segregation resistance (sive)	Segregation	SR1	≤ 20	%

3.2.1. Effect of fiber addition on the slump flow of SCGC

The slump flow test is a key assessment tool used to evaluate the ability of fresh concrete to flow uniformly and fill formwork without segregation. This test specifically measures the horizontal flowability of concrete, which is crucial for ensuring that the material achieves proper compaction and stability under various casting conditions. When fibers are added to the concrete mix, its flow properties are significantly affected. An increase in fiber content correlates with a decrease in flowability, which can be attributed to the greater surface area occupied by the fibers. This phenomenon enhances the bonding between the fibers and the concrete matrix, resulting in higher cohesion and ultimately restricting the material's ability to flow freely [60].

As demonstrated in various studies, including research on SCGC, this trend is clearly observed. As the fiber percentage increases, the slump flow diameter decreases, indicating reduced flowability [61]. Regression analysis can validate a linear relationship between fiber content and slump flow, confirming that higher fiber percentages consistently lead to lower flowability [62]. This negative correlation can be expressed through linear equations, where the slope values reflect the inverse relationship. A negative slope indicates that an increase in fiber content results in a decrease in slump flow measurement, highlighting the increased viscosity introduced by the fibers [63].

Fig. 5 illustrates this trend in SCGC, showing that as the fiber content increases, the slump flow diameter becomes smaller, indicating reduced flowability. The regression analysis of the data confirms a linear relationship between fiber percentage and slump flow, where higher fiber content results in lower flowability. This relationship is represented by the negative slope values in Equations (1)-(8), while the correlation coefficient, which approaches 1, reinforces the strong association between fiber content and concrete flowability.

In this context, x represents the fiber content percentage, while y denotes the slump flow value, typically measured in millimeters. The observed negative gradient across all equations further confirms that increasing fiber content leads to a reduction in slump flow. This behavior results from the increased cohesion within the concrete mix, which limits its ability to achieve optimal flow characteristics. While the slump flow results for SCGC generally comply with [27] standards, the study by [32] indicates that when fiber content exceeds 1%, the flowability criteria are not met. The following linear equation represents the relationship between fiber percentage and slump flow:

[14]	$y = -22x + 707.33$	$R^2 = 0.9356$	(1)
[31]	$y = -44x + 722$	$R^2 = 0.9906$	(2)
[32]	$y = -160x + 758.57$	$R^2 = 0.9053$	(3)
[35]	$y = -42.8x + 799.1$	$R^2 = 0.9878$	(4)
[34]	$y = -57.049x + 805.74$	$R^2 = 0.9526$	(5)
[33]	$y = -26x + 787$	$R^2 = 0.9657$	(6)
[37]	$y = -51.286x + 734.86$	$R^2 = 0.9587$	(7)
[30]	$y = -22x + 673.33$	$R^2 = 0.9578$	(8)

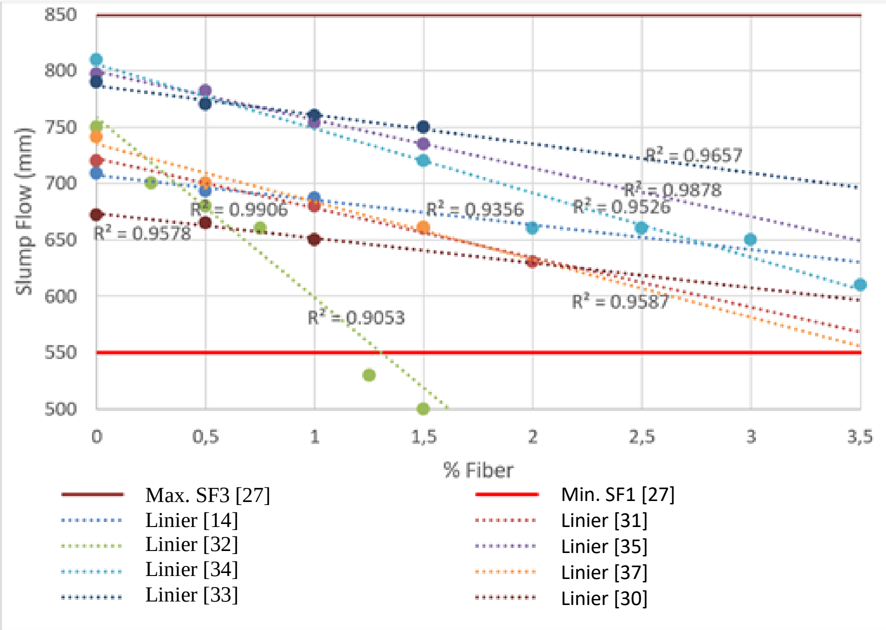

Fig. 5. Effect of fiber addition on the slump flow of SCGC

3.2.2. Effect of fiber addition on the T_{500} slump flow of SCGC

The T_{500} slump flow test evaluates the ability of fresh SCGC to spread to 500 mm without segregation, using a spreading table and Abrams cone. The recorded time reflects concrete viscosity, where increasing fiber content leads to a longer slump flow time (T_{500}), as shown in Fig. 6. This correlation is strong, with an R^2 coefficient above 0.9, forming a positive quadratic curve, as demonstrated in equations (9)-(16). Studies confirm a significant quadratic relationship between fiber volume fraction (x) and T_{500} SCGC (y), highlighting the nonlinear interaction between fibers and geopolymer concrete flow. The coefficients in these equations indicate how fiber type and quantity affect SCGC flow, reflecting variations in fiber properties, testing methods, and experimental design [64]. In addition to influencing flow behavior, fibers also enhance concrete strength and ductility, making them crucial for SCGC optimization [65].

[14]	$y = 0.1x^2 + 0.07x + 2.66$	$R^2 = 1$	(9)
[31]	$y = 0.3636x^2 + 1.1273x + 5.0727$	$R^2 = 0.9273$	(10)
[32]	$y = 1.5048x^2 + 1.0143x + 2.8167$	$R^2 = 0.9471$	(11)
[35]	$y = 0.4x^2 + x + 1.95$	$R^2 = 0.9848$	(12)
[34]	$y = 0.3183x^2 – 0.2484x + 2.4132$	$R^2 = 0.9646$	(13)
[30]	$y = 2x^2 - x + 4$	$R^2 = 1$	(14)
[33]	$y = 7E\text{-}15x^2 + 0.28x + 2.79$	$R^2 = 0.98$	(15)
[37]	$y = 0.0667x^2 + 0.1667x + 3.7$	$R^2 = 1$	(16)

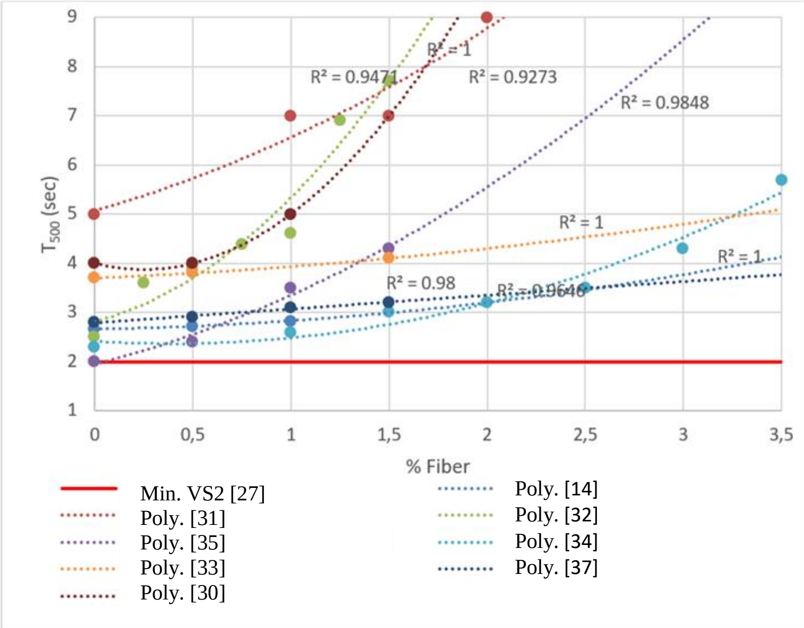

Fig. 6. Effect of fiber addition on the T_{500} slump flow of SCGC

3.2.3. Effect of fiber addition on the V-funnel flow of SCGC

The V-funnel test is a widely used method for assessing the viscosity of concrete mixtures. This test is conducted by pouring fresh concrete into a V-shaped funnel and measuring the time required for the concrete to flow out. In this context, x represents the fiber volume fraction (%) added to the concrete mix, while y indicates the V-funnel flow time (seconds), which reflects the concrete's ability to flow under the influence of gravity. Fig. 7 illustrates the relationship between fiber content and V-funnel flow time, showing that as fiber content increases, the flow time also increases. This indicates that the addition of fibers significantly affects the flowability of SCGC, making it more resistant to smooth, unrestricted flow.

Regression analysis confirms a strong linear relationship between fiber percentage (x) and V-funnel flow time (y), with all equations (17)-(21) exhibiting positive slope values. This means that higher fiber content results in longer flow times. The high correlation coefficient (R^2 close to 1) further reinforces this relationship, highlighting the crucial role of fibers in modifying the viscosity of the concrete mixture.

[14]	$y = 2.92x + 11.017$	$R^2 = 0.9579$	(17)
[32]	$y = 5x + 7.7643$	$R^2 = 0.9232$	(18)
[34]	$y = 1.7057x + 5.4389$	$R^2 = 0.8504$	(19)
[30]	$y = 9x + 17.167$	$R^2 = 0.9959$	(20)
[37]	$y = 0.33x + 11.165$	$R^2 = 0.9945$	(21)

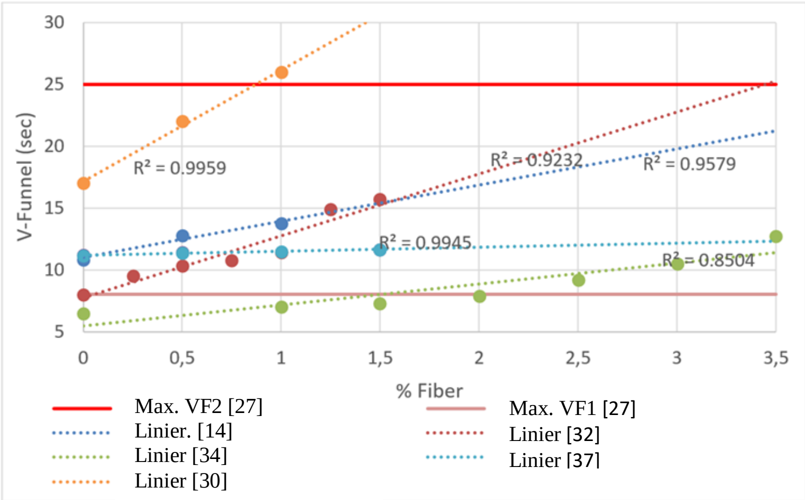

Fig. 7. Effect of fiber addition on the V-funnel flow of SCGC

3.2.4. Effect of fiber addition on the L-Box ratio of SCGC

The L-Box test, also known as the Swedish Box, is a tool used to evaluate the passing ability of concrete mixtures. This tool features an L-shaped design, consisting of vertical and horizontal sections, and is equipped with a liftable cover that allows the concrete to flow through. To simulate real-world conditions, steel reinforcement is placed near the cover, replicating the challenges that concrete mixtures face when passing through reinforcement during casting.

In this analysis, the variable x represents the fiber volume fraction (in percentage), while y denotes the L-box ratio, indicating how well the concrete can flow through obstructions while maintaining uniform consistency. Fig. 8 illustrates the relationship between fiber content and the L-box ratio, showing that as the fiber percentage increases, the L-box ratio decreases. This suggests that higher fiber content reduces the mixture's ability to pass through obstacles.

Further regression analysis supports these findings, revealing a linear relationship between fiber percentage and the L-box ratio, with negative slope values in Equations (22)-(27). This confirms that higher fiber content results in a lower L-box ratio, meaning that mixtures with higher fiber percentages are more likely to struggle when passing through reinforcement. Therefore, it is crucial to balance fiber content in the mix design to ensure that the concrete meets the required workability and passing ability, particularly in applications with complex structural elements.

[37]	$y = -0.08x + 0.985$	$R^2 = 0.9877$	(22)
[35]	$y = -0.038x + 0.926$	$R^2 = 0.9627$	(23)
[34]	$y = -0.033x + 0.9193$	$R^2 = 0.9885$	(24)
[14]	$y = -0.02x + 0.9033$	$R^2 = 1$	(25)
[30]	$y = -0.64x + 0.9433$	$R^2 = 0.9184$	(26)
[31]	$y = -0.0657x + 0.8914$	$R^2 = 0.701$	(27)

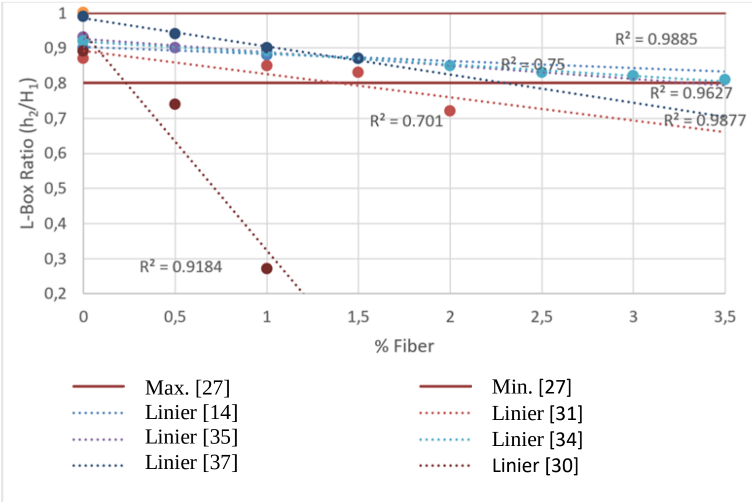

Fig. 8. Effect of fiber addition on the L-Box ratio of SCGC

3.3. Hardened properties of SCGC with added fibers

3.3.1. Effect of fiber addition on the compressive strength of SCGC

This analysis in Fig. 9 demonstrates the effect of fiber content on the compressive strength of SCGC. The presented equations (25)-(31) utilize quadratic regression models, where x represents the fiber volume fraction (%) and y denotes the compressive strength (MPa). The results show a negative quadratic relationship, meaning that while fiber addition initially enhances compressive strength, an excessive amount leads to a decline. This suggests that moderate fiber incorporation improves crack resistance and structural integrity, but excessive amounts hinder compactness due to fiber agglomeration and reduced workability [66].

The reliability of these findings is supported by high R^2 values (0.75 to 1), confirming that quadratic regression accurately represents experimental trends. [14], [37], and [30] reported $R^2 = 1$, indicating a perfect fit with their data, while other studies also show strong correlations. Variations in regression coefficients likely stem from differences in fiber types, mix proportions, and testing methods, yet all studies reinforce the necessity of an optimized mix design to balance fiber reinforcement and workability for peak SCGC performance.

These insights emphasize the complex relationship between fiber content and mechanical properties, highlighting that an optimal fiber dosage exists for maximizing compressive strength without compromising workability. Consequently, this analysis stresses the importance of carefully calibrated fiber proportions to maintain both structural integrity and performance in SCGC applications.

[31]	$y = -1.1409x^2 + 4.2392x + 49.359$	$R^2 = 0.7584$	(25)
[33]	$y = -9.6x^2 + 21.864x + 31.972$	$R^2 = 0.9939$	(26)
[37]	$y = -10.667x^2 + 23.333x + 30$	$R^2 = 1$	(27)
[35]	$y = -2x^2 + 6.32x + 58.86$	$R^2 = 0.9952$	(28)
[14]	$y = -3.2x^2 + 7.2x + 61$	$R^2 = 1$	(29)
[34]	$y = -0.0997x^2 + 2.0285x + 65.613$	$R^2 = 0.9224$	(30)
[30]	$y = -10.48x^2 + 13.92x + 36.13$	$R^2 = 1$	(31)

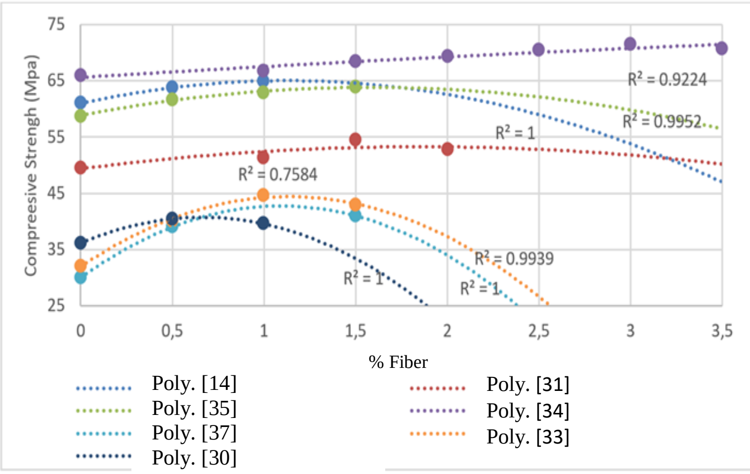

Fig. 9. Effect of fiber addition on the compressive strength of SCGC

3.3.2. Effect of fiber addition on the split tensile strength of SCGC

The analysis presented in Fig. 10 illustrates the effect of fiber content on the splitting tensile strength of SCGC. Since geopolymer concrete is generally brittle with low tensile strength, evaluating the influence of fiber incorporation is crucial to understanding its ability to resist cracking. Fibers act as reinforcements within the concrete matrix, bridging micro-cracks and enhancing tensile capacity. In this analysis, x represents the fiber volume fraction (%), indicating the percentage of fibers added to the concrete mix, while y denotes the splitting tensile strength (MPa), which measures the material's resistance to tensile forces. The linear regression models derived from multiple studies demonstrate a positive linear relationship between fiber content and splitting tensile strength, as seen in the equations proposed by [31], [37], [34], and [30]. These equations show that as fiber volume increases, the tensile strength of SCGC also improves, with high R^2 values (ranging from 0.7484 to 0.9815) confirming the accuracy of these models in representing the observed data. This trend suggests that incorporating fibers significantly enhances SCGC's tensile performance, making it more resistant to cracking and improving its structural integrity. However, an optimal fiber dosage should be carefully determined to balance workability, strength, and durability in construction applications. The findings from the regression analysis reveal a strong positive linear relationship between the fiber content and the splitting tensile strength of SCGC. The equation that describes this relationship can be observed below:

[31]	$y = 0.6771x + 2.8857$	$R^2 = 0.7484$	(32)
[37]	$y = 0.9x + 2.6$	$R^2 = 0.9643$	(33)
[34]	$y = 0.6463x + 3.9978$	$R^2 = 0.8381$	(34)
[30]	$y = 2.52x + 4.57$	$R^2 = 0.9815$	(35)

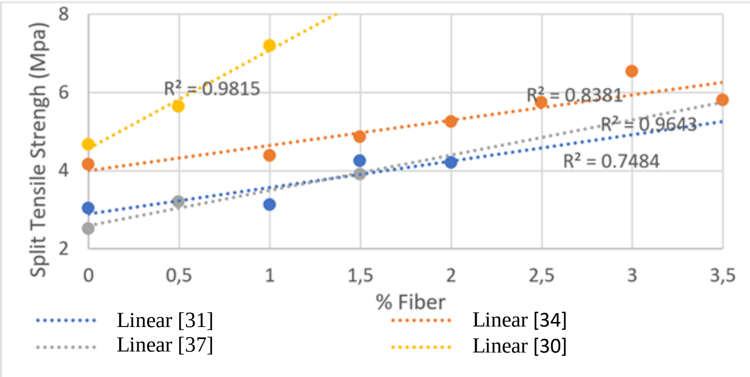

Fig. 10. Effect of fiber addition on the split tensile strength of SCGC

3.3.3. Effect of fiber addition on the flexural strength of SCGC

Flexural strength refers to the capacity of a concrete specimen to resist bending forces, essentially measuring its indirect tensile strength. This is determined through a bending test, where a concrete block is placed horizontally on the pressure table of a flexural testing machine, and the load is applied until failure. The addition of fibers in composite materials can significantly enhance flexural strength by reinforcing the internal structure and distributing stress more evenly [67]. Fibers act as reinforcements that help resist tensile stress at the bottom of the material when subjected to a bending load. Moreover, fibers contribute to inhibiting crack propagation, thereby increasing the material's resistance to failure [68,69]. Therefore, in evaluating flexural strength, not only factors such as geometry and stress distribution should be considered, but also the presence of fibers as reinforcing elements that improve the material's resistance to deformation and damage [70]. The analysis presented in Fig. 11 illustrates the effect of fiber content on the flexural strength of SCGC, a critical parameter for assessing resistance to tensile stress induced by bending loads. The fibers introduced into the concrete mix act as reinforcement elements, enhancing crack resistance and augmenting the material's flexural capacity. In this analysis, x represents the fiber volume fraction (%), while y indicates the flexural strength (MPa) of the SCGC. The quadratic regression equations developed by various researchers demonstrate a non-linear relationship between fiber content and flexural strength. Notably, R^2 values range from 0.6048 to 0.9571, reflecting that the quadratic regression models effectively represent the experimental data trends.

The findings suggest that flexural strength initially improves with increasing fiber content. However, at higher dosages, a decline in flexural strength emerges, implying that while fibers enhance resistance to bending forces, excessive additions may result in fiber agglomeration, thereby reducing overall reinforcement effectiveness. Thus, attaining a well-balanced mix design is paramount to optimize the benefits of fiber reinforcement without compromising workability and durability [71, 72].

The importance of a balanced mix design is further emphasized in the literature, where the synergistic effects of fiber reinforcement on various mechanical properties have been well-documented. Research indicates that proper fiber distribution can significantly enhance the flexural strength of SCGC, which is critical for applications requiring robust structural integrity [72]. The relationship between fiber content and flexural strength in SCGC follows a negative quadratic pattern, which is represented by the equation below:

[31] $$y = -0.1655x^2 + 0.5351x + 3.9129 \quad R^2 = 0.6048 \quad (36)$$

[37] $$y = -0.2x^2 + 0.86x + 4.73 \quad R^2 = 0.9571 \quad (37)$$

[34] $$y = -0.0085x^2 + 0.8274x + 5.3696 \quad R^2 = 0.8845 \quad (38)$$

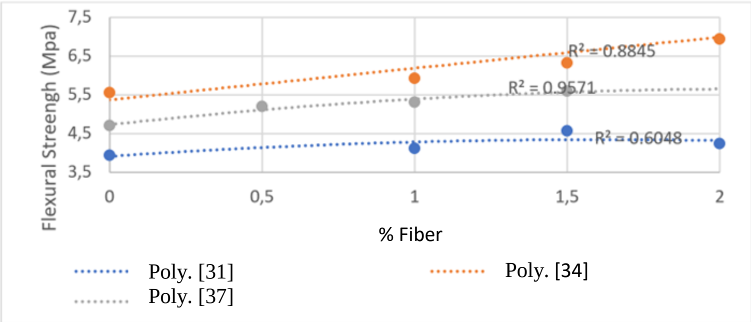

Fig. 11. Effect of fiber addition on the flexural strength of SCGC

4. CONCLUSIONS

The findings derived from both the bibliometric analysis and literature review on the topics discussed in this paper can be summarized as follows:

- The bibliometric analysis highlights that research on Self-Compacting Geopolymer Concrete (SCGC) reinforced with fibers is still in its early stages. Most publications in this area have emerged in 2022, suggesting a relatively recent surge in interest. This opens up ample opportunities for further exploration and development of SCGC with fibers in the coming years.
- A variety of waste materials have been investigated as potential binders to replace conventional cement in SCGC. This approach not only addresses sustainability concerns but also supports the use of industrial byproducts to reduce environmental impact.
- Steel fibers remain the most commonly used reinforcement in current SCGC research. However, there is considerable potential for further studies exploring the use of alternative fibers, which could provide different mechanical and durability characteristics.
- Research on SCGC has focused on varying types of fibers, their shapes, aspect ratios, and volumetric fractions. It has been found that the inclusion of fibers significantly influences both the fresh and hardened properties of SCGC, improving certain characteristics such as tensile strength and crack resistance.
- Despite the positive impacts on mechanical properties, the incorporation of fibers into SCGC tends to decrease some of its fresh properties, such as workability and flowability, due to the fibers' resistance to the movement of the mixture.
- In terms of mechanical performance, the addition of fibers leads to a noticeable increase in splitting tensile strength. However, the effect on compressive and flexural strength is more complex; while fiber addition can enhance these properties up to a certain point, beyond this optimal fiber content, further fiber inclusion can reduce compressive strength, possibly due to fiber clumping or poor distribution in the matrix.

These conclusions underline both the potential and the challenges of incorporating fibers into SCGC, offering numerous avenues for future research to enhance the material's performance and explore alternative reinforcement methods.

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