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Mechanical Properties of Fiber-Reinforced Self-Compacting Geopolymer Concrete Using Lightweight Aggregate under Microwave Curing Condition

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ABSTRACT

Geopolymer composites are remarkable binding materials due to their sustainability and recyclability. This study investigates the behaviour of Self-Compacting Geopolymer Concrete (SCGC) as a viable alternative to conventional concrete. It examines the effects of adding Lightweight Coarse Aggregate (LWCA) and Steel Fibre (SF) under different curing environments on the fresh and hardened properties of SCGC. Curing was applied using microwave and ambient environments. SF was added at 0%, 0.5%, 1%, and 1.5% of the binder content. Natural coarse aggregate was partially replaced with LWCA by weight at 0%, 33.3%, 66.67%, and 100%. The SCGC mixes were analysed in both fresh and hardened states to evaluate their mechanical properties. Results showed that higher LWCA and SF ratios led to more viscous and cohesive mixes. SCGC specimens under ambient curing exhibited lower compressive, flexural, and tensile strengths compared to those under microwave curing. Microwave-cured samples demonstrated improved performance, with a 38.09% increase in compressive strength for the B6 mix and a 28.02% enhancement in flexural strength. The highest tensile strength (TS) was 4.67 MPa for the B3 mix with 1.5% SF. However, using 66.67% LWCA under microwave curing resulted in a 27.9% reduction in TS. The study recommends using industrial-scale microwave curing and recycled materials, such as steel fibres and LWCA, to produce cost-effective and sustainable SCGC.

Keywords: Geopolymer; SCGC; Flexural; Compression; Microwave; Concrete

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1. Introduction

The emission of greenhouse gases, leading to global warming, is becoming one of the world's most pressing problems for sustainable development. Global policies that balance development and environmental protection across nations are necessary for managing climate change, as is a profound engagement with green energy technologies. Due to the necessary calcination process of raw materials (such as limestone), the use of traditional concrete contributes 10% of global anthropogenic carbon dioxide emissions, in line with the megatrends in infrastructure modernisation [1,2].

Hundreds of tons of debris are produced each year as a result of the deconstruction of old structures during redevelopment and specific industrialisation activities, which is a growing worldwide concern [3].

Geopolymer manufacture is an environmentally benign alternative to conventional Portland cement, as it can save up to 80% of energy and reduce carbon dioxide emissions by 50% to 80%, in contrast to the energy-intensive and highly polluting cement production process [4–7].

Alkali-activated binders, also known as geopolymers, are a type of cementitious material binder that are created when an alkali activator reacts with a dry aluminium silicate component, such as pulverised fly ash (PFA), Ground granulated blast fibre slag (GGBFS), clays, or volcanic materials. Since the 1970s, geopolymers have been the subject of extensive research. They have been linked to several economic engineering projects and international patents, and their superior mechanical and thermal qualities have been demonstrated [8,9]. Illustrating their possible substitution for Portland cement in specific, low-risk uses [10].

The creation of geopolymers offers a viable alternative to traditional cement production, significantly reducing greenhouse gas emissions. While geopolymers provide significant advantages over conventional cement in specific areas, their extended maintenance duration and gradual strength growth have emerged as the primary obstacles to their practical implementation. The most popular method for accelerating the geopolymerization process is traditional thermal curing such as oven, water, and air curing).

In recent years, scientists have conducted various research investigations on the production and utilisation of geopolymers using materials such as fly ash, silica fume, and volcanic ash as precursors, along with alkaline compounds and binders– molds were exposed to ambient, microwave, and heating energy [11,12].

Utilisation of various materials as lightweight aggregate (LWA) by geopolymerization. Fly ash (FA) and silica fume are used as precursors, fine LWA are more porous and lighter than natural LWA, while their properties are similar to natural LWA. Many studies utilise various waste as a coarse lightweight (CLWA) and fine light weight (FLWA) aggregate in geopolymers; LWA has been applied by using waste by many techniques [13].

Most geopolymer studies apply sodium hydroxide NaOH and sodium silicate Na_2SiO_3 as an activator [14].

Curing conditions are applied through many techniques like: 1. sintering, 2. Autoclaving, and 3. cold bonding. Sintering consumes high energy as aggregates are cured at a temperature range of 1000–1300 °C [15].

Conventional curing methods, such as sintering and autoclaving, impart radiation to the material's surface before transferring it via conduction to its core. This creates a temperature differential in the material, giving it heterogeneous features. Microwave curing, which relies on the conversion of energy rather than heat transmission, is another option. Because microwaves may pass through the material and transmit energy, resulting in dispersed volumetric warming, this curing approach allows for fast and homogeneous heating. To support users in fast-track construction, electromagnetic radiation is transformed into heat energy, which improves reaction kinetics and speeds up the strength increase process [16].

This study explores the effects of steel fiber reinforcement and lightweight aggregates on the performance of self-compacted geopolymer concrete SCGC under microwave curing conditions. The novelty of this research lies in its investigation of the synergistic interactions between steel fibers, lightweight aggregates, and microwave curing factors, which can significantly enhance the mechanical and thermal properties of geopolymer concrete. Microwave curing, known for its rapid and efficient heat transfer, offers potential advantages over traditional curing methods, particularly in improving the early-age properties and energy efficiency of SCGC [17]. The incorporation of lightweight aggregates further contributes to improved

workability and reduced density, making the material more suitable for applications requiring reduced dead load, such as in high-rise buildings and precast components [18].

By advancing the understanding of how microwave curing, lightweight aggregates, and fiber reinforcement interact in SCGC, this study provides valuable insights into optimising this composite material for sustainable, high-performance concrete applications. This research significantly extends the current knowledge base by offering a novel approach to curing, material composition, and performance enhancement in fiber-reinforced self-compacting geopolymer concrete.

The application of microwave curing in geopolymerisation processes has emerged as an innovative method to accelerate the curing time and improve the material's properties. Microwave curing offers the advantage of providing uniform heating, leading to improved homogeneity of the final product. Several studies have investigated the effects of microwave curing on the microstructure, strength, and setting time of fiber-reinforced SCGC, highlighting potential improvements in both mechanical and durability characteristics [19].

According to studies, the early compressive strength of air- and water-cured geopolymers was considerably lower than that of the oven-cured geopolymer. Moreover, raising the temperature would increase the geopolymer's strength [20].

By subjecting geopolymers to high temperatures and high pressures, steam curing helps to promote geopolymerization by decreasing efflorescence [21]. Application on a large scale may be challenging because solar hardening, which strongly depends on weather and geographic location, can yield robust geopolymers at negligible solidification costs and low carbon emissions, replacing high-temperature hardening [22]. In addition to raising the temperature, exogenous materials can improve the characteristics of geopolymers. When nanoparticles are properly incorporated into geopolymers, the geopolymerisation process can be accelerated, material porosity can be decreased, and the interfacial transition zone can be improved [23]. The majority of geopolymer curing techniques still require a lengthy repair period to enable adequate geopolymerization and strength growth. In the realm of geopolymers, technologies that facilitate rapid strength growth are highly desirable. Microwaves are a form of electromagnetic radiation with frequencies between 300 MHz and 300 GHz. They mainly cause dielectric heating by ionic conductivity and the absorption of electrical energy by polar molecules [24,25].

Food processing, medical sterilisation, chemical and polymer synthesis, and other fields extensively utilise microwave irradiation [24,26]. Microwaves offer several benefits over traditional heating methods, including consistent heating, reduced heat loss, enhanced reaction kinetics, quick reaction times, and high energy efficiency [27–29]. Furthermore, it is well known that conventional heating techniques produce the "skin effect," which is better for surface heating and is described as the quick evaporation of water from the exterior surface of the heated materials [30–32]. As a result, the high temperature gradient makes it difficult to accomplish uniform heating, and the heated materials experience considerable energy loss due to heat conduction and convection [33].

When compared to conventional heating, the distinct heating patterns of microwave irradiation can produce more consistent heating, which makes them an alluring property to improve the geopolymerization process [34,35]. The rapid heating that can result from polar molecules, such as water molecules, absorbing microwave energy could encourage the growth of internal thermal stress in geopolymers [33]. By favourably coupling to materials with strong microwave absorption capabilities, MW heating at the molecular level can produce unique characteristics for selective heating when irradiating materials with diverse dielectric properties, in addition to volumetric heating [36].

Heat conduction wastes a lot of energy and time, whereas selective heating prevents this [35]. On the other hand, incorrect microwave irradiation can cause geopolymers to break on the surface, thereby weakening their structural integrity [37,38].

There are three primary mechanisms for microwave warming: ionic conduction, dipolar polarization and interactive polarization [39]. According to the dipolar polarisation process, polarised molecules are rotated in an electric field, causing the dipoles to reorganise and become polarised. In addition to water, which is a popular microwave-absorbent material, other polar or ionic chemicals. such as salt, acid, alkali, or ionic liquids can also be added

to increase the medium's MW absorption level [40]. Friction is created, and the geopolymer's interior is heated when the dipolar reorientation is adjusted in a rapidly altering electric field [24,29]. High-frequency electric fields cause ionic conduction, which is the movement of ions in materials that are unable to keep up with the electric field's frequency. This causes the ions to vibrate, producing heat [41,42].

Neither study examined the combined use of steel fiber reinforcement and lightweight aggregate in SCGCs under microwave curing technology. Consequently, the goal of this paper is to study the combined use of steel fiber reinforcement and lightweight aggregate in SCGCs under microwave curing conditions technology for the synthesis of geopolymers.

2. Experimental Work

2.1. Materials

Using the slag GGBFS with low calcium content of fly ash (FA) as the raw materials, naturally coarser aggregates (NCA), light coarse aggregates (LWCA) as fillers, sodium hydroxide NaOH aqueous solution as alkaline, diluted sodium silicate (SS) mixture used as a binder, and diluted SP with distilled water solution as a workability indicator are the materials that will be utilized in making the SCGC specimens. All materials used in this paper were supplied by local suppliers.

The rationale behind selecting specific percentages of steel fiber and lightweight aggregate in self-compacted geopolymer concrete SCGC primarily aims to enhance mechanical properties, durability, and workability. The percentage typically ranges between 0.5% and 2% by volume, as higher percentages may adversely affect workability [39]. The typical range is between 20% and 40% by volume, as higher amounts may compromise strength and stability [43–45].

Fly ash (FA) of type F- according to the ASTM C618, was applied as a binders factor. This paper applies a fineness modulus of 4% and FA with relatively poor calcium, specifically 2.29% specific gravity [46]. The chemical composition percentage of FA is listed in **Table 1**.

Table 1. FA chemical analysis.

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO
%	1.59	62.34	21.13	7.16	2.39
Component	**SG**	**Na_2O**	**K_2O**	**LOI**	**SO_3**
%	2.29	0.37	3.38	1.57	0.11

2.1.1. GGBFS

GGBFS is a byproduct of the blast furnace used in the metallic alloy industry. It consists of between 30% and 40% of silicon dioxide SiO_2 and roughly 40% calcium oxide CaO. After the slag was cleansed, it was immediately submerged entirely in water to generate GGBS [9].

2.1.2. Aggregate

Crushed limestone rocks with a specific gravity of 1.2 were used, as the LWCA came from the west region of Iraq, specifically the Al-Nebaai quarry in Anbar province. Coarse Aggregate With a maximum theoretical size of 19 mm and a specific gravity value of 2.46 for fine coarse aggregate FA and 2.75 for natural coarse aggregate NCA, it was employed to create SCGC. **Figure 1 shows** the aggregates' characteristics. It was reassembled after being sieved using a sieve examination to meet ASTM C330 grading requirements. The maximum nominal size of NCA was applied to LWCA Iraq [47].

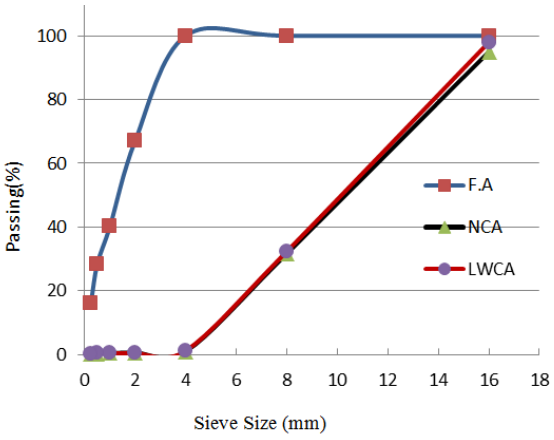

Figure 1. The gradation of aggregate.

2.1.3. Steel fibers SF

In this study, SF was added to increase the flexibility of SCGC. SF were Copper-coated. SF has 13.0 and 0.2 mm of length and diameter, respectively (**Figure 2**). The

SF quality is listed in **Table 2**. Three different SF ratios were used: 0%, 1%, and 1.5%.

Table 2. The SF characteristics.

Parameter	Description
Feature	Coated Cooper
Tensile Strength	> 2400 MPa
Melt Temp.	1500 °C
Mass Density	7860 Kg/m^3
Form	Uniform Straight
Length	13.0 ± 1.0 mm
Diameter	0.2 ± 0.02 mm

Figure 2. The SF used in research.

2.1.4. Usable Water

Tap water was used throughout this work in mixing concrete without any additives.

2.1.5. Activator

The alkali activator is a mixture of sodium hydroxide (SH NaOH) and sodium silicate (SS Na_2SiO_3) [48]. The SS was provided by a nearby regional store within the Anbar governorate, Iraq [7]. The sodium hydroxide utilised had a purity of 97%–98% and a molar concentration of 12 M, which was considered the best quality for SCGC's physical efficiency [49].

2.1.6. Superplasticiser

Superplasticiser (SP) of the poly carboxylic-ether class with a pH value of 5.7 and relative density S.G. of 1.07 will be one of the constituents in the mixture. This kind of SP is liquid and complies with ASTM's 2005 standards [22]. The Dosage weight ratios of SP at 8%, 10%, and 12% were used. **Table 3** shows the significant characteristics of SP.

Table 3. Primary characteristics of SP.

Pproperty	Description
Color	Dark brown / black liquid
Specific gravity	1.07 at 250C
Air entrainment	< 1%
Chloride content	< 0.1%
Alkaline content	< 3%

2.1.7. Alkali Solution

An alkali-solution to binder proportion of roughly 0.35 to 0.40 was made to improve the mechanical properties of the geopolymer concrete. It was determined that SH/SS ratios between 1.5 and 2.5 were appropriate. Using marketed binder (500 kg/m^3, SH 57 kg/m^3), and fine gravel FA (850 kg/m^3), all dry solid materials FA, SF, and GGBFS and aggregates were thoroughly mixed. To the premixed solid product, a liquid mixture of SP and activator with more water was added [50]. The materials used in the investigation are listed in **Figure 3**.

Figure 3. Raw materials of SCGC combination.

2.2. Mix Design

The purpose of the laboratory program is to determine how SF, LWCA, and curing environment (CC) affect SCGC's fresh and hardened properties. In this program, LWCA, represented by broken limestone rocks, will par-

tially substitute the naturally occurring coarse aggregate. Water will dissolve the NaOH flake to create an alkaline aqueous solution.

The solution of sodium hydroxide will be cooled to 27 °C to 30 °C, and, it will be blended with Na_2SiO_3 to create the alkali activator solution. Eighteen SCGC mixes will be designed and prepared as part of the experimental program.

The coarse and fine aggregate will be combined in a concrete mixer for approximately one minute. Subsequently, the concrete mixer was filled one at a time with the mixed powder raw ingredients, the alkali activator solution, and superplasticiser.

After the mixing procedure was finished, three layers of the newly created slurry were poured into moulds that had been previously oiled. Specimens were prepared for testing to determine their mechanical and transport properties, in order to assess the efficacy of the LWCA-SF reinforced SCGC.

The mixes B1MC - B9MC were left in the mould for 24 hours before being cured in a microwave for 10 minutes at 350 Watts. The other specimens, B1AC-B9AC, were stored in surrounding air conditioning (AC), which is 25 ± 2 °C ambient 25 ± 2 °C for a total of 28 days prior to the test. **Table 4** presents the mixture proportions of the SCGC samples.

Table 4. SCGC sample mixtures proportioning.

Mixes ID	Curing Condition	Binder 500 Kg/m³		Aggregate				NaOH Kg/m3			Sodium Silicate	W	SP	SF	
		FA	GGBFS slag	F.A	NCA	LWCA									
		Kg/m³	Kg/m³	Kg/m³	Kg/m³	Kg/m³	%	Flak	Water	M	Kg/m³	%	%	%	%
B1MC	Microwave	250	250	909.36	772.64	0	0	23.74	40.00	12	160.56	30	8	0	0
B2MC					772.64	0		23.74	40.00		160.56		10	78.5	1
B3MC					772.64	0		23.74	40.00		160.56		12	117.8	1.5
B4MC					257.52	515.11	66.67	23.74	40.00		160.56		8	0	0
B5MC					257.52	515.11		23.74	40.00		160.56		9	39.3	1
B6MC					257.52	515.11		23.74	40.00		160.56		12	117.8	1.5
B7MC					0	772.64	100	23.74	40.00		160.56		8	0	0
B8MC					0	772.64		23.74	40.00		160.56		10	78.5	1
B9MC					0	772.64		23.74	40.00		160.56		12	117.8	1.5
B1AC	Ambient	250	250	909.36	772.64	0	0	23.74	40.00	12	160.56	30	8	0	0
B2AC					772.64	0		23.74	40.00		160.56		10	78.5	1
B3AC					772.64	0		23.74	40.00		160.56		12	117.8	1.5
B4AC					257.52	515.11	66.67	23.74	40.00		160.56		8	0	0
B5AC					257.52	515.11		23.74	40.00		160.56		9	39.3	1
B6AC					257.52	515.11		23.74	40.00		160.56		12	117.8	1.5
B7AC					0	772.64	100	23.74	40.00		160.56		8	0	0
B8AC					0	772.64		23.74	40.00		160.56		10	78.5	1
B9AC					0	772.64		23.74	40.00		160.56		12	117.8	1.5

2.3. Curing

Mixes B1MC- B9MC were stored by placing them into microwave curing condition MC at 350 Watt for 10 minutes, until the test 24 hours in the moulds and 10 minutes in the MW . Mixtures B1AC- B9AC were left to cure in a normal environment (25 ± 3oC) for 28 days prior to the test. The work technique flow chart is displayed in **Figure 4**.

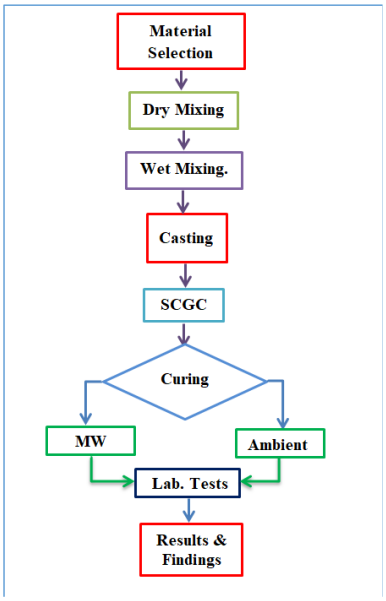

Figure 4. Process diagram of process technique.

2.4. Testing of SCGC

Fresh Properties of SCGC

The fresh values of SCGC mixtures were determined in accordance with EFNARC, as shown in **Table 5** [51]. Calculations were made to determine the SCGC, including filling capacity V-Funnel, slump flow and flowing abilities L-box.

Table 5. Test findings of fresh SCGS characteristics.

Mix. No.	Slump Flow mm	T_{50} mm	V-funnel Flow Second	L.box %
B1	630	1.43	6.09	0.832
B2	600	1.84	6.85	0.835
B3	520	16.91	7.46	0.913
B4	590	2.38	8.25	0.815
B5	460	3.95	8.69	0.901
B6	395	4.28	9.48	0.982
B7	580	1.41	6.35	0.844
B8	530	6.3	7.45	0.892
B9	490	6.86	10.92	0.984

Slump Flow Test

Before setting up, the SCGC slump flow diameter (SFD) is used to assess the uniformity of the fresh SCGC. It is done to evaluate the workability and, in turn, the flowability of the newly created SCGC. It may also indicate that a batch was not well combined. The popularity of the test can be ascribed to its simple equipment requirements and technique. The slump test is used in the field to ensure homogeneity for different SCGC loads [51].

V-funnel Test

The V-funnel analysis can be used to measure the SCGC's filling ability, also known as flow ability. The funnel is filled with SCGC, and the time it takes for the SCGC to flow through the apparatus is noted [52].

L-box Test

This test assesses the flow of the SCGC. The apparatus consists of a box that is rectangular box with a sliding door that slides which divides its vertical and horizontal portions.. The reinforcement bar is positioned vertically in front of the door. The shape of the box is an "L". The door is lifted to let the SCGC move into the horizontal place once the flow stops. It displays the resting-state slope of the SCGC. This indicates the amount of concrete that cannot pass through the bars or passing ability [51].

2.5. Mechanical Characteristics of SCGC

2.5.1. Compressive Strength Test

The SCGC were characterised and evaluated by measuring CS. The CS is used as a measure of other mechanical properties of concrete, as it usually correlates well with other measurements of the material. Cubes with 100x100x100 mm were produced from various mixture designs and put through a 3000 KN universal compression analysis instrument in accordance with BS EN 12390-3 [51]. Three tests and duplicates of each SCGC mixture were conducted. Results demonstrated that SCGC can attain notably high CS when cured at room temperature or by microwave curing. The use of microwave activation, as opposed to a natural cure, resulted in a greater CS since it accelerates the geopolymerisation process. Slag and fly ash added to the matrix significantly raise the CS of the SCGC when cured at room temperature [53]. **Figure 5** shows the compressive strength test machine.

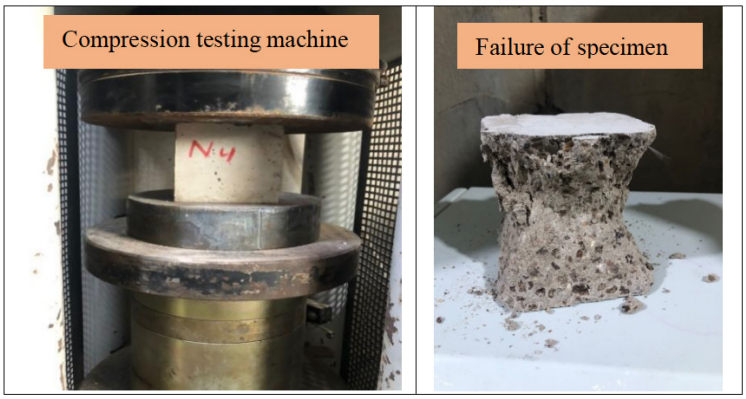

Figure 5. Compressive strength test.

2.5.2. Tensile Strength Test

The TS of concrete and its outcomes are more reliable than those of other tests. The TS was run according to ASTM C496M [54]. For All SCGC mixtures, three cylindrical samples, each measuring 100 x 200 mm, were averaged to determine SCGC's tensile strength (**Figure 6)**. The cylindrical sample is loaded horizontally between two plates of the provided testing equipment until the failure manifests as separating throughout the diameter [55].

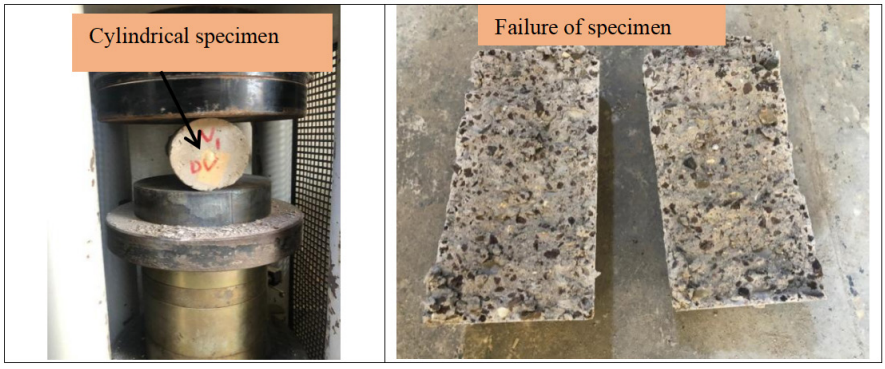

Figure 6. Splitting tensile strength test.

2.5.3. Flexural Strength Test

Flexural strength (FS) is the measurement of bending resistance. The term "modulus of rupture" might be applied to the FS. Foure-point loading is applied to the specimen, whose dimensions are 100×100×500 mm until it breaks (**Figure 7)**. The testing was done in compliance with ASTM C78-04 [56].

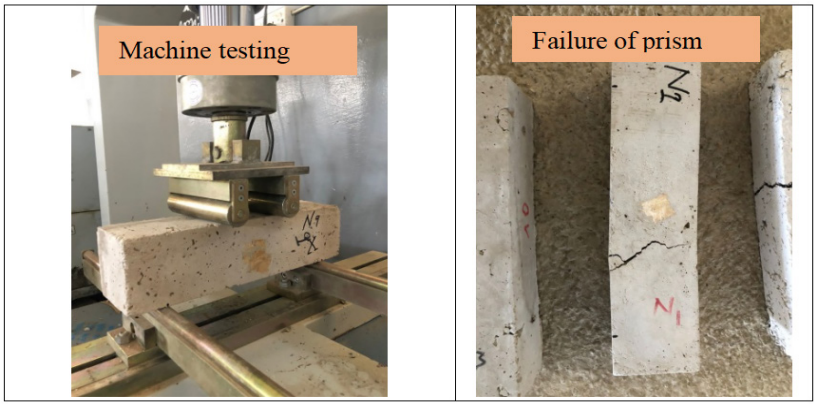

Figure 7. Flexural strength test.

3. Results and Discussions

3.1. Fresh Properties of SCGS

Table 5 displays the SCGS characteristics. The results show remarkable variations in SCGS fresh characteristics. Slump Flow ranged from 395 mm (B6) to 630 mm (B1), indicating differing workability. B3's high T_{50} (16.91 mm) suggests cohesion issues, while the increasing V-funnel times (6.09–10.92 second) reflect lower viscosity. Increased L-box ratios (e.g., 0.984 for B9) indicate better filling but potentially higher fines. Optimising mix characteristics is crucial to balance fluidity and stability for structural applications.

The maximum SFD 630mm was achieved with a mixture of 100% NCA and 0% SF. When SF was added at 1% and 1.5%, respectively, SFD dropped from 630 mm 100% NCA to 600 and 520 mm.

When 0% of SF and 100% of NCA were mixed, the biggest SFD, 630mm, was recorded. SFD degraded from 630 mm with 100% of NCA to 600 and 520 mm, respectively, with the addition of SF by 1% and 1.5%.

The replacement NCA of 100% by LWCA and the addition of 1.5 % of SF led to SFD of 490 mm, and SFD was raised from 490 mm to 580 mm and 530 mm when SF was mixed by 0% and 1.0%, respectively.

SFD dropped from 630 mm with 100% NCA to 600 and 520 mm when SF combined by 1% and 1.5%, respectively. This result is consistent with the findings of Al-Jumaili, who reported that the incorporation of steel fibers leads to a noticeable reduction in workability due to increased internal friction and reduced flowability [50].

The mixing of 33.33 % of NCA and 66.67 % from LWCA with 1.5% of SF has a minimum SFD of 395 mm. SFD raised with the addition of 33.33 % NCA and 66.67% of LWCA from 395 mm to 590 mm and 460 mm when SF mixed by 0.0 % and 1.0 %, respectively.

The substitution of 100% of NCA by LWCA and the addition of 1.5 % of SF has an SFD of 490 mm. This led to raising SFD from 490 mm to 580 mm and 530 mm, as the SF was mixed by 0.0 % and 1.0 %, respectively.

According to EFNARC requirements, all the SFD findings met the SF2 group, which is acceptable for a wide range of reinforced sections slab, columns and beams.

The improved V-funnel flow time and T_{50} time increased as a result of SF and LWCA, which is comparable to the SFD outcomes.

However, based on EFNARC criteria, both T_{50} and V-funnel values in the study were deemed satisfactory [52]. The percentage of SF and LWCA have an adverse impact on the SCGC's flowability, based on the T_{50} time period data. Mixtures with have 100% LWCA and 1.5% of SF have the maximum T_{50} time duration. SFD values were dropped by adding SF and LWC, although the T_{50} time, L-Box ratio and V-funnel flow time were increased.

A larger quantity of SF and LWCA in mixtures leads to being more viscous and cohesive, but the fluidity and flowability of SCGC mixes decreased. Furthermore, all SCGC mixtures meet the SCGC standards based on the EFNARC.

Nonetheless, it became evident that the combinations with higher SF and LWCA were more cohesive than those with lower SF, and that the addition of GGBFS enhanced both segregation and bleeding resistance [57–59].

3.2. Hardened Characteristics of SCGS

3.2.1. Compressive Strength

This paper examines the SCGC by applying fly Ash/slag as a binder. The SCGC is cured with normal air lab temperature AC and microwave curing (MC) for10 minutes at 350 watt conditions listed in **Figure 8**. The specimens cured into AC had lower CS than those of MC. The CS of specimens cured with MC, in contrast to the AC ones raised about 37.76%, 25.50%, 18.71.% , 27.56%, 28.17%, 28.31%, 39.01%, 31.55%, and 29.13%, respectively . The Maximum CS value was 52.13 MPa for B3 when the SF ratio was 1.5%. The Max CS increment was for B7; this demonstrates microwave's enhanced activation of geopolymerisation via Dielectric heating for polar molecules (H_2O, OH^-), improved dissolution of aluminosilicate precursors and improved polycondensation kinetics, as well as indicated that the CS dropped when raising LWCA. The unreacted fly ash component caused the CS to drop, which led to severe dehydration [22]. The maximum result of CS for each AC and MC was for B3 mixes, which were 42.37 MPa and 52.13 MPa, respectively. The minimum CS result was for the B7 mixture for both AC and MC, which were 12.02 MPa and 19.84 MPa, respective-

ly. Raising the LWCA quantities lead to decrease the CS of SCGC due to the minimum activity of fly ash (FA) [60]. The improvement of CS values was due to the durable and extremely robust linkage between the fibers and matrix during microwave curing conditions, which made the mixing of SF in the SCGC mixture more successful than with standard binders [61,62].

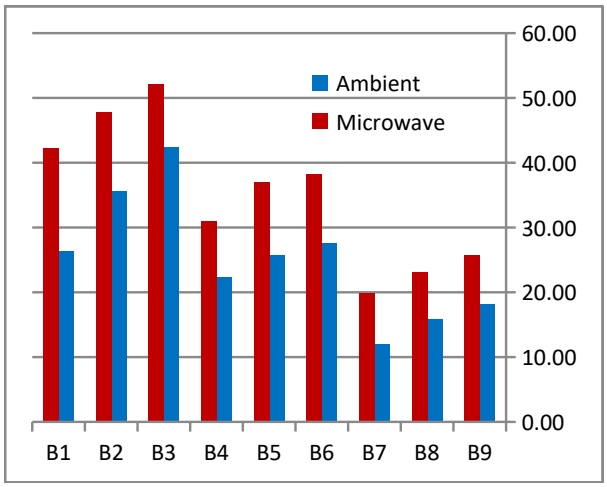

Figure 8. CS valus of spiecmans.

3.2.2. Flexural Strength

The performance of SCGC cured with AC and MC for 10 minutes at 350 watt conditions indicated in **Figure 9**. The specimens subjected to AC had lower FS than those of MC. The FS of specimens subjected to MC compared with AC ones raised about 24.41%, 18.84%, 26.24%, 27.36%, 24.49%, 28.02%, 20.09%, 17.89%, and 16.40%, respectively. FS increase for B3, B6, and B9 once SF quantity was increased. However, FS dropped after the raising LWCA ratio, and it also dropped as a result of uncombined fly ash, leading to a maximum level of dehydration [63].

The maximum increment result of FS was for M6 mixture MC conditions with 28.02%, which corresponded to 3.19 MPa. The lowest FS increment result for B9 mixture MC conditions was 16.04%, corresponding to 1.92 MPa–significant strength augmentation results from the microwave curing condition. In a similar vein, this indicates microwave's improved the FS at 4.24 MPa (26.2% increase) owing to the synergistic combination of these factors. Increased geopolymerisation rate, enhanced fiber-matrix connection, efficient fiber dispersion, uniform gel development and decreased microcrack development as well as longer cure time improved the geopolymerisation processes and produced stronger results [64].

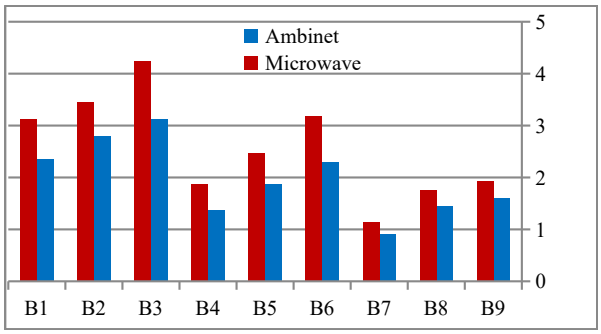

Figure 9. FS valus of spiecmans.

3.2.3. Tensile Strength

The performance of the SCGC subjected to AC and MC for 10 minutes at 350 watts is displayed in **Figure 10**. The specimens cured with AC had low tensile strength (TS) compared to MC ones. The tensile strength of samples cured to MC compared to the AC ones, increased by about 27.20%, 15.3%, 27.09%, 25.43%, 15.66%, 27.60%, 12.22%, 13.86%, and 14.18%, respectively. The maximum TS values were raised for B3, B6, and B9 when the quantity of SF increased due to balanced chemistry and superior fiber-matrix bonding. The TS dropped when increasing the LWCA. The TS values dropped because of uncombined fly ash FA due to a high level of dehydration [63,64]. These enhancements were achieved through microstructural modification, which consists the homogeneous formation of a gel and fewer microcracks, with B6 demonstrating the largest improvement (27.6%), showing microwave curing effectiveness and improved matrix density.

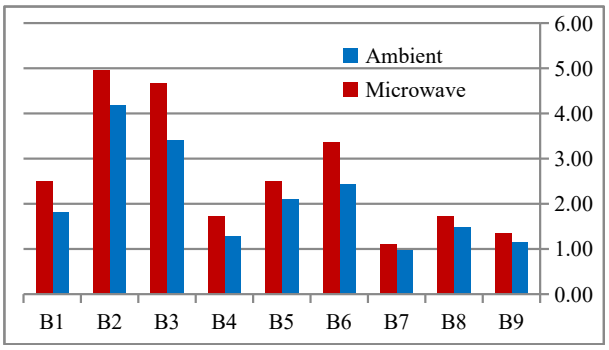

Figure 10. Splitting tensile strength.

The highest increment value of the TS for MC conditions was for M6 mixture, which was 27.6% with 3.37

MPa. The low increment TS result for MC conditions was 12.22% with 1.11 MPa for the B7 mixture. This was due to an incomplete moisturising process and increased blanks in SCGC mixes [41,65,66].

Fiber-reinforced self-compact geopolymer concrete SCGC has shown significant improvements in mechanical properties, including compressive strength, flexural strength, and fracture toughness. The addition of steel fibers can reduce brittleness and increase the material's resistance to cracking, making SCGC more suitable for structural applications.

3.3. Microwave Mechanism

Dissolution, speciation equilibrium, gelation, reorganisation, polymerisation, and hardening are all steps in the production of geopolymers, also known as geopolymerization [65]. During the entire geopolymerisation process, microwave radiation may facilitate the synthesis of geopolymers (**Figure 11**). Initially, aluminate and silicate monomers are produced through the hydrolysis and alkali degradation of aluminosilicate parent materials [67]. This action causes resistance and inner heat in the geopolymer as the polarity of water molecules absorbs microwaves and modifies their dipolar orientation in a rapidly changing electric field [67,68]. Therefore, it accelerated the decomposition of the geopolymer's basic ingredients. Si^{4+} and Al^{3+} compounds are then coverted into oligomers, and condensation results in the formation of a gel with a more expansive network structure. By polycondensation, the expanding gel continues to recombine, creating an amorphous aluminosilicate structure [42]. The water in the geopolymerization dehydration cycle can evaporate more quickly when geopolymer blocks are microwave-processed. Following the completion of the initial dissolution reaction, the growing gel can be continuously reorganised in a short period using the microwave process. The dehydration process of the polycondensation reaction forms the three-dimensional aluminosilicate network structure, which speeds up the densification of geopolymers and improves their mechanical properties. Microwave curing has been demonstrated to accelerate the curing process of geopolymer concrete, reducing the time required for strength development. This is highly beneficial in industrial-scale production, where faster curing can lead to increased throughput and lower production costs. Additionally, microwave curing has been found to improve the homogeneity of the material, resulting in more consistent strength and performance across different batches.

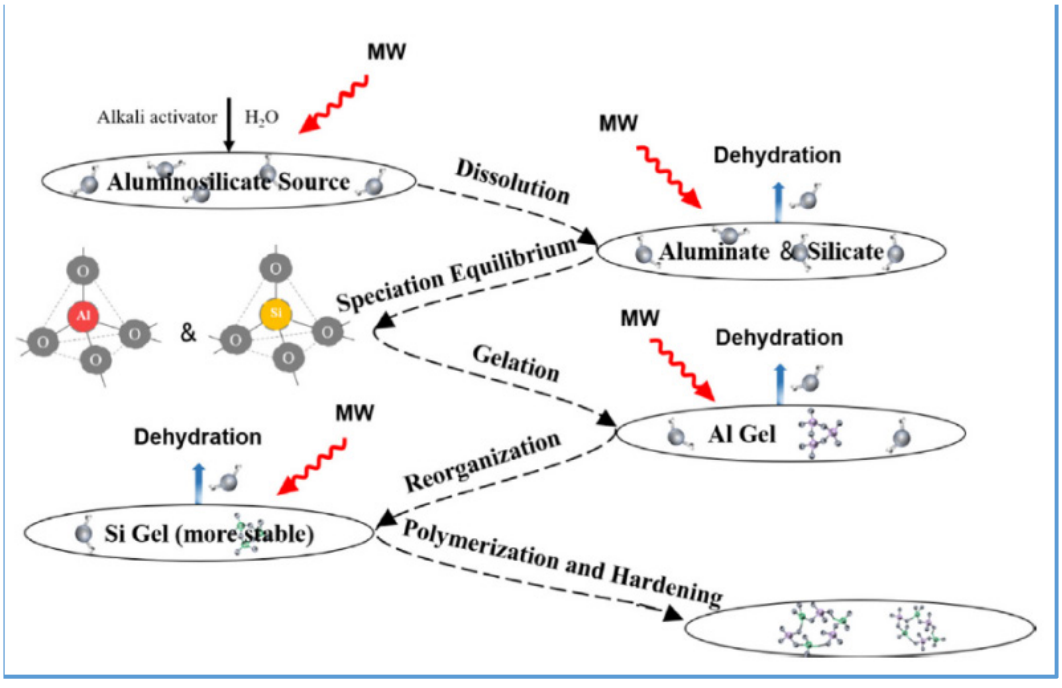

Figure 11. Mechanisms of MW irradiation to geopolymer production [69].

4. Conclusion

The conclusion of this research includes:

1- SF and LWCA inclusion dropped the SFD value and L-box ratios of SCGC mixtures. The mixtures had a higher ratio of SF and LWCA were more viscous and stronger; as the ratios of the GGBFS developed, the liquidity and flow-ability of SCGC blends dropped and their resistance to bleeding and segregation enhanced.

2- All mixtures of SCGC satisfied the EFNARC criteria and standard for passing-ability and flow-ability.

3- The compressive strength CS of the SCGC placed under microwave curing MC conditions was higher than that of the ambient curing AC conditions. The CS results for the B3 mixture were enhanced by 52.13%.

4- The SF limits the fresh parameters, but it improves the SCGC's mechanical parameters. The improved behaviour of mechanical parameters is evident, with CS being 52.13 MPa at 1.5% SF under MC conditions.

5- The LWCA had a clear impact with fresh characteristics. The LWCA has little impact on performance and minimised the mechanical characteristics; LWCA minimized the FS; the FS was 3.11 MPa and 1.88 MPa for a partial substitute of 66.67% and 0.0% respectively under MC condition.

6- The tensile strength of SCGC placed into microwave curing MC had a low Tensile Strength than of MC ones, The better TS result was 4.67 MPa for the M3 mixtures with an SF ratio of 1.5%. While the TS indicated increasing about 27.6% and 14.18% when using the LWCA as partial replacement under MC condition of 66.67% and 100%, respectively.

7- Sustainability Benefits: The combination of steel fiber and microwave curing in SCGC offers a more sustainable solution for the construction industry. SCGC contributes to reducing the environmental impact of construction activities. Moreover, the energy efficiency of microwave curing can further enhance the sustainability of this approach, providing both economic and ecological advantages over traditional cement-based products.

8- According to the results, microwaves speed up the hydration process due to thermodynamic effects. This finding highlights the potential for controlling reactions with microwaves.

9- As a result, it is recommended to use the microwave curing condition with industrial scale to produce the SCGC and reuse scrapes like steel and valuable materials such as LWCA in SCGC as a cost-effective, economical and environmentally beneficial resource.

5. Limitations and Future Research Directions

5.1. Limitations

There are some limitations facing the research; the challenges include :

- Energy Usage: Microwave curing consumes 30% more energy than other procedures.
- Mixing Sensitivity: Effectiveness changes greatly by formulation.
- Scalability: Present findings are confined to lab-scale specimens.

5.2. Future Research Directions

There are some future research directions and recommendation:

1. Hybrid Curing Methods (microwave/ambient).
2. Nanoscale Modification - Use nano-SiO_2 to improve low-performing blends.
3. Industrial Up-scaling: Pilot experiments using full-scale components of the structure.

Author Contributions

Author Contributions: Conceptualization, A.S.N.; Methodology, A.S.N.; Writing—original draft preparation, A.S.N.; Supervision, S.B. and Z.I.; Writing—review and editing, S.B. and Z.I. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

No new datasets were generated or analyzed during the current study. Data sharing is not applicable due to the nature of the research.

Conflicts of Interest

The authors declare no conflict of interest.

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