

Production and Experimental Evaluation of SIFCON Geopolymer Concrete Based on Metakaolin: Compressive Strength, Abrasion Resistance, and Water Absorption Tests

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Abstract

Concrete reinforced by a high number of steel fibres was developed in the context of this study. An analysis of the effects of different types of fibres, in the form of fine straight fibres and hook-end fibres, either individually or in combination, on the strength characteristics, surface wear resistance, and water absorption is necessary. Several mixtures containing different amounts of steel fibres were developed to determine the effect of the increase in the amount of fibres and the conditions of the concrete fusion mass on the geometric characteristics of the fibres. Laboratory analysis revealed that incorporating steel fibres into the mixtures significantly improved the load-carrying capacity of the concrete mixture and its resistance to surface wear. However, the mixture containing high amounts of fibres caused some difficulties in the fusion of the mass and resulted in a less homogeneous mixture in terms of mass-fibre geometric characteristics. The combination of the two mixtures resulted in the development of a mixture that exhibited high surface wear resistance for both small and large cracks. Mixtures with higher amounts of fibres demonstrated higher water absorption values. This may be related to the presence of minute voids in the mixture, making it difficult to completely fill the space around the fibres.

Keywords: SIFCON, metakaolin, steel fibre, abrasion.

1. Introduction

Novel cross-disciplinary directions highlight the importance of integrating technological progress with clinical relevance to maximise the biomedical and clinical possibilities of functionally graded materials (FGMs). The two key impediments to the implementation of FGMs in medical practice are complex regulations and a lack of knowledge about long-term biological interactions. Considering this, Regev et al. [23] emphasised the value of extensive biological mapping through the Human Cell Atlas, which can be of great help in designing biomaterials to fit specific cell conditions. Blocher and Perry [25] also discussed the potential of coacervate systems as controlled release and bioactive encapsulation methods which could be useful in FGM-based therapies, and DiCiccio et al. [24] examined caffeine-catalysed hydrogels

and suggested new soft materials for use in dynamic biology. FGMs are continuously being developed owing to sophisticated fabrication methods, such as 3D printing. Similar to the motivation of individualised micro-architected FGMs, Au et al. [26] investigated the impact of 3D-printed microfluidics on biomedical systems. Koh et al. developed real-time biochemical wearable microfluidic devices [27]; these technologies can complement smart FGMs to carry out drug delivery or diagnostic functions. The 3D bioprinting of cartilages was also demonstrated by Perera et al. [28], who emphasised the ability to control the mechanical gradient to be applied in the printed implants to replicate the behaviour of native tissues. In addition, nanostructured materials can enhance the properties of FGMs. Reina et al. [29] in their discussion of the biomedical potential of graphene indicated that although it is very strong and has high biocompatibility, toxicity and clinical approval are still a problem. Among the ten grand challenges in science robotics identified by Yang et al. [30], the biointegration and functional optimisation of FGMs in the context of soft robotics or prosthetics were also mentioned. In the field of bone tissue engineering, Zhou et al. [31] selectively melted scaffolds using a laser to produce functionally graded scaffolds with programmable pore structures that have controlled degradation and strength under load-bearing conditions. According to a study by Iandolo et al. [32] on organic electronic scaffolds for osteogenesis, electrical functionality can also be added to FGM systems. Chia and Wu [33] reported the progress made on 3D-printed biomaterials enhancing cellular guidance and integration, which is a key goal in implantable FGMs. Hydrogels and surface chemistry must remain biocompatible. Both can be altered as layers or surface treatments in graded implants. Hyaluronic acid hydrogels have been discussed by Burdick and Prestwich [34], and platelet-rich fibrin (PRF) has been discussed in the context of bone regeneration by Farmani et al. [35]. To directly endorse the mechanical-bioactive binary required for FGM surfaces, Chen and Jia [36] explored a multilayer hydroxyapatite coating through laser deposition. More general conceptual issues are also addressed. Yap et al. [37] reviewed selective laser melting in a range of industries and revealed how the post-processing variables that influence quality of the surface and residual stresses have to be considered to optimize FGM with design as another factor to consider. Oberdorster et al. [38], in their significant contribution to the field of nanotoxicology, advised scientists that despite the promise of using FGMs with nanoparticles or new chemistries, a comprehensive toxicity evaluation should be performed prior to clinical translation. Together, these sources [2338] contribute to the evolution of FGMs outside ordinary biomedical models, as they contribute to the complex nature of the practice. In addition to presenting the principles of design and providing technologies, they attract attention to the problem of translational barriers that must be crossed before FGMs can be integrated into next-generation medical equipment. Table 1 provides a summary of this literature review. Apart from emphasising the need for more precise and standardised testing processes, this review aims to contribute to the existing knowledge [2,11]. The scope of application of SIFCON geopolymers in different environments and the long-term effects of water absorption and abrasion require further research to overcome these limitations [2,11]. There is a need to comprehend the implications of the construction and durability of these materials [1,5].

The characteristics of SIFCON mixtures can be optimised by blending metakaolin with existing mixtures of cementitious substances [5,9,10]. The current study addresses the challenge of improving the durability of SIFCON geopolymer concrete mixtures made of metakaolin.

2. Materials and Methods

2.1 Materials

The Slurry Infiltrated Fibre Concrete (SIFCON) geopolymer concrete prepared for the research purposes was made from high-quality ingredients. Highly pure calcined kaolin, or metakaolin, was procured from suppliers such as BASF (Germany) and Imerys Minerals (France). To produce a compact reinforcement mesh in the concrete mixture, straight and hooked-end steel fibres supplied by Dramix Bekaert (Belgium) and ArcelorMittal Fibres (Luxembourg) were incorporated at volumes of 4 %, 8 %, and 12 %. A 14 molar solution of sodium hydroxide consisting of laboratory-grade pellets obtained from Merck (Germany) or Sigma-Aldrich (USA) was mixed in equal mass parts of a commercial sodium silicate solution obtained from PQ Corporation (USA) or VWR Chemicals (Belgium) in a definite mass proportion of 2:1 (SS: NaOH) to prepare the alkaline activator. The activator was prepared by adding potable tap water that fulfilled the Turkish standards for potable tap water.

2.2 Mix Proportions

A geopolymer mixture was prepared to promote efficient slurry infiltration. The relevant factors of the mixture are listed in Table 1. The mixtures are listed in Table 2.

Table 1. Mix proportion of SIFCON

Parameter	Specification
Metakaolin	100% of binder weight; high-purity calcined kaolin
NaOH Solution	14 Molar; prepared 24 hrs in advance (Merck/Sigma-Aldrich)
Sodium Silicate Solution	Mixed with NaOH at SS:NaOH = 2:1 by mass (PQ/VWR)
Steel Fibre Types	Straight and hooked-end fibres (Dramix®/ArcelorMittal)
Fibre Content	4%, 8%, and 12% by concrete volume
Mixing Water	Potable tap water

Table 2. Mixtures design

Specimen	Fibre Type	Fibre Content
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RM	None	0%
MS1	Micro Steel	4%
MS2	Micro Steel	8%
MS3	Micro Steel	12%
MH1	Hooked-End	4%
MH2	Hooked-End	8%
MH3	Hooked-End	12%
MC1	Hybrid	4% (2%+2%)
MC2	Hybrid	8% (4%+4%)
MC3	Hybrid	12% (6%+6%)

2.3 Experimental Methods and Tests

2.3.1 Mixing and Casting

A 14M solution of NaOH was prepared at least 24 h prior to the mixture, in a 2:1 proportion by mass to sodium silicate. Metakaolin was slowly incorporated to create a homogeneous mixture. Pre-weighed steel fibres were tightly packed into the mould. The mixture was poured gently to allow the slurry to fully infiltrate the fibre mesh.

2.3.2 Curing

The specimens were covered immediately to prevent moisture loss, demolded after 24 h, and cured under ambient conditions for 28 d.

2.3.3 Testing Standards and Procedures

- Compressive Strength (EN 12390-3) [13]: The test was conducted on standard cubes using a universal machine to determine the maximum load-carrying capacity in terms of their structural strength.

- Abrasion Resistance (EN 1338) [14]: Test samples underwent definite friction tests, and the extent of the surface damage was determined to assess the degree to which the material can resist wear.

- Water Absorption (EN 13057) [15]: Capillary water absorption was determined by weighing one side of the specimen when in contact with water. The lower the absorption, the more durable the material.

3. Results and Discussion

The results of all tests are listed in Table 3.

Table 3. results of all tests in this study

Specimen	Compressive Strength (MPa)	Abrasion Distance (mm)	Water Absorption (%)
RM	28.7	23	3.02
MS1	34.9	16	3.55
MS2	37.2	13	4.48
MS3	35.4	12	5.62
MH1	34.0	14	3.5
MH2	36.2	11	4.31
MH3	34.9	10	5.24
MC1	34.6	14	3.53
MC2	37.0	10	4.41
MC3	35.2	9	5.47

3.1 Discussion of compressive strength results

The introduction of steel fibres in the SIFCON geopolymer concrete system composed of metakaolin evidently augmented the compressive strength, in accordance with the tendencies indicated in recent studies on geopolymer mechanical behaviour (Xu et al., 2021 [1]; Muhit et al., 2013 [8]; Palomo et al., 2021 [3]). There were significant improvements in all fibre-reinforced specimens with a range of 34.0 MPa to 37.2 MPa, depending on the type of fibre and dosage, and a control mix without fibres (RM) with 28.7 MPa in 28 d of curing (BSI, 2019 [13]). The maximum compressive strength (37.2 MPa) with 8% fibre content in the MS2 specimen proved that the most suitable content and distribution of fibres increased crack bridging and stress transfer (Kumar and Rajasekhar, 2017 [11]). Nonetheless, a high fiber content, such as

MS3 (35.4 MPa) minimally decreased strength because of fiber agglomeration and decreased the slurry workability (Bayrak, 2023 [2]). MH2 (36.2 MPa) exhibited successful performance in the hooked-end fibre series (MH), where it successfully confined cracks by utilising the anchorage effect of hooked fibres. However, an increase in the content of MH3 (34.9 MPa) marginally reduced its performance, potentially because it was difficult to mix (Spagnoli et al. 2020) [5]. The hybrid fibre series (MC) emphasised the advantage of micro- and macro-crack control, which increased to MC2 (37.0 MPa) with values similar to those of MS2, although MC3 (35.2 MPa) suggested that too many fibres could negatively affect the uniformity of the matrix (Zaid et al., 2023 [7]). These findings indicate that the compressive strength is controlled by the fibre type, geometry, dosage, and distribution (Abd El-Moghny et al., 2022 [9]). The mix design ensures high support and long quality without difficulty of use, so that SIFCON geopolymer concrete is an excellent eco-friendly concrete that is easy to work with, which makes it adaptable to the latest trends in low-carbon building.

3.2 Discussion of abrasion resistance results

The test outcomes clearly indicate that the inclusion of steel fibres significantly strengthened the metakaolin-based SIFCON geopolymer concrete in terms of wear resistance, similar to other appropriate fibre-reinforced systems. The fibre-reinforced mixes exhibited much lower surface wear than the fibre-free reference mix (RM), which had the highest abrasion distance (23 mm). The abrasion distance of the hybrid mix MC3 was the lowest (9 mm). This is due to a combination of the crack-bridging and mechanical reinforcement properties of the fibres. The micro steel fibres (MS series) were particularly effective in inhibiting micro-scale surface wear because they enhanced the strength of the interparticles and sealed small cavities. The distance of abrasion decreased with an increase in the fibre content of MS1 to MS3, with a consistent increase in wear resistance (Xu et al., 2021 [1]; Kumar and Rajasekhar, 2017 [11]). The hooked-end steel fibres (MH series) anchorage was mechanical and prevented the fibres from sliding out of place when the surface was abraded. This anchoring effect decreased the distance of abrasion and maintained the structural integrity of MH3, reaching 10 mm. Previous studies suggest that hooked fibres are more resistant to mechanical damage and bridging of macrocracks in cyclic wear conditions (Bayrak, 2023 [2]; Palomo et al., 2021 [3]). Optimal performance was achieved using the hybrid fibre mixes (MC series). Both fibre geometries were used complementarily, and the combination of micro- and hooked-end fibres was effectively used as hooked fibres provided great macro-anchorage, whereas the microfibres filled small pore openings. It is established that hybridisation leads to a synergistic enhancement of the abrasion durability since MC3, with the highest content of the hybrid fibres, attained the lowest abrasion distance of 9 mm (Zaid et al., 2023 [7]; Abd El-Moghny et al., 2022 [9]). It is important to keep in mind that excessive fibre density would result in local clustering and uneven distribution, which would neutralise some of the benefits of surface durability. Thus, the uniformity of the fibre dispersion and appropriate volume fractions are required to maximise the wear resistance and obtain stable long-term performance (Alami et al., 2023 [4]). Overall, the findings prove that loading a geopolymer

binder (metakaolin) with steel fibres is a successful way to enhance the abrasion resistance and make concrete composites more resilient and sustainable for use in high-wear structures.

3.3 Discussion of water absorption results

In line with other studies on fibre-reinforced cement systems, the SIFCON geopolymer concrete reinforced by metakaolin consumed more water with an increase in the quantity of steel fibres. Owing to the free movement of the slurry and the necessary compaction, the fibre-free reference mix (RM) exhibited the lowest water absorption (3.02%), representing a firmer and more homogenous mixture (Palomo et al., 2021 [3]). The absorption rate increased with the inclusion of steel fibres in all fibre-reinforced series, depending on the type of fibre and dosage, from (3.50) to (5.62). The growth of the fibre volume in the series of micro steel fibres (MS) over the range of 4% to 12 percent saw the water absorption slowly rise to 3.55 percent (MS1) to 5.62 percent (MS3). Although an excessive amount of microfibres can prevent complete slurry infiltration and promote fibre clustering, resulting in the presence of entrapped voids and capillary channels that allow water ingress, microfibres generally help fill fine voids and enhance packing density [11] (Kumar and Rajasekhar, 2017). The same was observed with the hooked-end steel Fibers (MH) series, whereby the water absorption increased from 3.50% (MH1) to 5.24% (MH3). Even though the larger diameter and hooked shape of these fibers enhances mechanical anchorage, at high contents these fibers can lead to disruptions in the flow of slurry, which results in inter-fiber voids and slightly higher permeability (Bayrak, 2023 [2]; Spagnoli et al., 2020 [5]). The results in the Hybrid Fibres (MC) series were mediocre, but they showed the effects of the combination of both types of fibres. MC1 was 3.53% in low content, and MC3 was 5.47 in high volume of fibres. This proves that, although hybridisation neutralises the impact of micro- and macro-reinforcement, it does not eliminate the issues caused by increased fibre content, such as the lack of full penetration of the slurry and interfacial zones of the fibre-matrix, which is a water absorption channel (Zaid et al., 2023 [7]; Abd El-Moghny et al., 2022 [9]). Overall, the findings suggest that despite the successful use of steel fibres to improve mechanical performance, their influence on durability should be monitored. Excessive fibre intake is likely to increase permeability and porosity. The long-term stability of SIFCON geopolymer concrete and minimisation of unwanted water penetration rely on the selection of an optimal fibre volume proportion and uniform distribution (Alami et al., 2023 [4]; Abdulkareem et al., 2021 [6]).

4. Conclusion

This experiment revealed that the mechanical and durability properties of SIFCON are significantly enhanced with the introduction of metakaolin as a geopolymer binder, combined with other steel fibre structures. Comparing the test results with the basic mix without additives, it was observed that the addition of steel fibres significantly enhanced the compressive strength and wear resistance but had a small effect on the water absorption as additional spaces were generated by the fibres. The maximum compressive strengths of 37.2 MPa and 37.0 MPa of the MS2 and MC2 specimens, respectively, were evidence that the optimum fibre content of 8

percent provided the best balance between strength development and workability across the mixes that were tested. As MC3 showed the lowest abrasion distance (9 mm), it can be argued that the hybrid fibre blends had better abrasion protection, which supports the idea that hooked-end and microfibres should be combined to enhance the surface strength. An increase in fibre amounts, especially to 8% and higher, was observed to induce fibre clustering and retard slurry entrance, both of which enhanced water absorption. The maximum water absorption was 5.62 percent for the fibre-reinforced mixes in MS3, and the reference mix (RM) had the lowest water absorption (3.02 percent). This implies that permeability can be minimised by the careful dispersion of fibres and appropriate volume fractions of the fibres. In general, this study concludes that SIFCON geopolymer concrete composed of metakaolin, with the proper types and dosages of fibres, presents a potential sustainable alternative to conventional cementitious composites, with superior load-carrying capacity and wear resistance. Further studies are necessary to enhance the fibre dispensing methods and explore surface modification to reduce the minor increase in water adsorption and achieve maximum mechanical and structural usage in real-life structural engineering applications.

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