UDK 625.821.5:52-334.2
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

INFLUENCE OF STEATITE POWDER ON THE MECHANICAL PROPERTIES AND MICROSTRUCTURE OF SUSTAINABLE CONCRETE

VPLIV STEATITNEGA PRAHU NA MIKROSTRUKTURO IN MEHANSKE LASTNOSTI TRAJNOSTNEGA BETONA

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Prejem rokopisa – received: 2025-05-05; sprejem za objavo – accepted for publication: 2025-06-15

doi:10.17222/mit.2025.1447

In the construction sector, one of the essential materials is cement, and a key component in making concrete is cement. Nevertheless, the energy-intensive process of cement manufacture depletes natural resources, raises CO_2 emissions, and has an undesirable effect on the environment. This has motivated specialists to explore appropriate cement alternatives to create sustainable cementitious materials. The objective of this study was to examine the use of steatite powder (SP) as a partial replacement for cement to minimize its adverse consequences on the environment, while maintaining the required properties of the concrete. In this work, the fresh properties, strength, and microstructural features were examined. Scanning electron microscopy (SEM) helped to validate the mechanical strength. Ordinary Portland cement (OPC) was replaced with SP in proportionsof 0 %, 5 %, 10 %, and 15 %. The slump cone test was utilized to measure the workability of the concrete mix. The results showed that as the ratio of steatite replacement increased, the slump values declined. The mechanical properties such as compressive strength, split tensile strength, and flexural strength were examined by considering the average samples for curing times of 7 d and 28 d. The inclusion of 5 % steatite powder produced good results for all the curing periods and revealed that it is an ideal mix for cement replacement. From the microstructure study, it was noted that the fine steatite particles sealed the voids and minimized the pore structure of the mixture, along with improving the interfacial transition zone (ITZ); hence, it produced a denser structure.

Keywords: steatite powder (SP), scanning electron microscopy and interfacial transition zone

V gradbenem sektorju je cement ključna sestavina za izdelavo betona. Energetsko intenziven postopek proizvodnje cementa izčrpava naravne vire, povečuje emisije CO_2 in ima neželen vpliv na okolje. To je inženirje spodbudilo k iskanju ustreznih zamenjav za cement in s tem postopke za izdelavo in uporabo bolj trajnostno naravnanih cementnih materialov. Cilj študije predstavljene v tem članku je bil preučiti uporabo steatitnega prahu (pretežno mineral imenovan lojevec oziroma magnezij-silikat-hidroksid) kot delno zamenjavo za cement. S tem bi zmanjšali negativne posledice za okolje, hkrati pa ohranili zahtevane lastnosti betona. V tej študiji so avtorji ugotavljali mikrostrukturne in mehanske lastnosti steatita. S pomočjo vrstične elektronske mikroskopije (SEM) so avtorji ocenili njegove morfološke in mehanske lastnosti. Navadni portlandski cement (OPC) so nadomestili s steatitnim prahom (SP) v različnih količinah (5%, 10% in 15%). Oblikovalnost izbranih svežih betonskih mešanic so ocenili s testom posedanja stožca. Rezultati so pokazali, da se je s povečevanjem vsebnosti steatitnega prahu posedanje stožca svežega betona zmanjševalo. Sledili so še mehanski preizkusi določitve tlačne, natezne in upogibne trdnosti betona po 7 in 28 dnevnem utrjevanju. Avtorji so s preiskusi ugotovili, da je optimalni dodatek k mešanici 5 % steatitnega prahu za obe izbrani obdobji strjevanja oziroma utrjevanja. Mikrostrukturne analize so pokazale, da drobni prašni delci steatita zapirajo praznine in tako zgoščujejo porozno strukturo mešanice in hkrati izboljšujejo medfazno prehodno območje (ITZ; angl.: interfacial transition zone). Posledično je nastala tudi gostejša struktura izdelanega betona.

Ključne besede: steatitni prah, elektronska vrstična mikroskopija, mejna in prehodna cona

1 INTRODUCTION

Concrete's strength, accessibility, cost and versatility in a wide range of structural applications make it among the most extensively used construction elements in the world.[1] The manufacturing of concrete requires a raw materials and natural resources in mass, and due to this the renewable assets are diminishing.[2] Cement production is an important contributing factor to global warming due to the greenhouse effect caused by the carbon dioxide generated during the manufacturing process.[3] Globally, the consumption of cement has increased by almost 9 % every year.[4,5] The manufacturing of cement and other industrialized areas will surely produce more carbon dioxide emissions annually due to the rapid rate of urbanization.[6] It has been noted that the cement sector generates significant greenhouse gas. Every metric tonne of Portland cement clinker discharged is proportional to around one metric tonne of carbon dioxide.[7] Because of its massive carbon footprint, cement cannot be recognized as a long-term sustainable component.[8] In an effort to mitigate its influence on the environment and improve the stability and durability of concrete, cement producers are searching for a replacement of the cementitious compound.[9] The application of concrete is now crucial to the

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adoption of green construction methods.[10] The concrete industry has implemented a number of initiatives to reduce carbon emissions.[11,12] One of the most feasible and widely utilized solutions is the partial replacement of cement with various supplementary cementitious materials (SCMs).[13–15] These include Ultrafine Ground granulated blast-furnace slag (UFGGBFS), fly ash (FA), metakaolin, rice husk ash, palm oil fuel ash, limestone powder, marble powder, talc, Rock dust, silica fume and Steatite powder etc.[16–20] Enhanced performance of that material is achieved by including mineral additives such as metakaolin and silica fume in the concrete.[21] Incorporating SCMs to cement improves its strength and serviceability.[22,23] The inclusion of SCMs into blended cement concrete has demonstrated increased mechanical and durability qualities.[24,25] The most effective ratio for getting the greatest outcomes was found to be 10 % talc to alkali-activated slag.[26] The overuse of SCMs can worsen various adverse environmental impacts and reduce material performance.[27] A method to select combinations that minimize adverse environmental consequences is to quantify the effects of the SCM-to-cement ratio.[28] Studies have proved that while compressive strength improved with a rise in talc, quartz, and lime sand, permeability and porosity decreased.[29] SP consists of the maximum amount of hydrated magnesium silicate and it gives a high degree of malleability due to its talc essence and it is extracted from metamorphic rock.[30,31] It is familiarly known as soapstone. SP is used in ceramics, paint, polymers, refractory materials and many other Multiple sectors due to its hydrophobic attributes and minimal surface energy.[32,33] About 60 % of byproduct is generated and leading to disposal constraints during the synthesis of SP.[34] Steatite has a low chemical attraction and high crystalline composition; therefore, it is applied in cement-based substances.[35] To enhance the particle reactivity, a new form of steatite was introduced as thermally treated substance and high in magnesium silicate known as Metasteatite.[36] Another material utilized to produce cementitious binder to strengthen the pozzolanic activity with mechanical properties such as magnesite and calcined steatite both contains struvite and magnesia.[37] The steatite powder is utilized in different special concretes such as self-compacting concrete, self-healing concrete, geopolymer concrete, etc. The workability was decreased when ultrafine natural steatite powder (UFNSP) was added because it raises the water requirement. However, it raises the compressive strength to some extent. The ideal improvement in strength was identified at a 15 % inclusion of steatite.[38,39] Similarly, in self-healing concrete replacing 15 % of steatite powder with cement gave the optimum result in compressive, tensile and flexural strength.[40] Since the UFNSP has a finer particle size and contains magnesium in the SCC mixes that are thus produced, the mechanical characteristics stay raised up to 20 % of the addition of UFNSP while developing their optimal strength at 15 % of UFNSP.[41] Studies show that gradually elevating the percentage of fly ash substituted with steatite powder leads to enhanced strength and 30 % of steatite powder is a desirable value.[42] The high strength values were exhibited while employing the GGBS (40 %) and UFNSP (10 %) when adding polypropylene fiber with 15 % of steatite.[43,44] In a special mortar like geopolymer, the inclusion of UFNSP fortifies the Alkali Activated mortar and creates a dense structure.[45] Some researcher found that, addition of carbon fibers with SP reduced the structural component weight and boosted the mechanical strength.[46] The Magnesium Silicate Hydrate (M-S-H) gel obtained during hydration process and support to minimizes the pores, seal the microcracks, improves the microstructure and durability features.[47] The mapping of the silicate and magnesium indicates diffusion throughout the surface, enabling it to create denser forms.[48] The structural integrity was elevated by sealing the voids through the fine substance of SP.[49] The incorporation of UFNSP reduces the flow and enhances the compressive strength by up to 20 %. Magnesium Silicate Hydrate (M-S-H) as well as Calcium Silicate Hydrate (C-S-H) formations are noticed through the microstructural behavior. Adding UFNSP to specimens increases their microstructure density, resulting in higher strength.[50] Significant improvements in mechanical characteristics were noted when UFNSP was replaced to the level of 15 %. Through SEM examinations it was possible to see M-S-H formation and the limitation of voids in the mix.[51] Many recent studies have examined the use of steatite powder in concrete, analyzing how it affects the material's fresh and hardened qualities as well as the ideal dosage and particle size distribution. The outcomes of these studies indicate that steatite powder may prove to be a viable substitute for conventional binder in concrete, potentially enhancing the material's workability, hardeness and durability.

2 EXPERIMENTAL INVESTIGATION

2.1Material

The main elements of the concrete are OPC grade 53 conforming to IS 12269:2013.[52] with the relative density of 3.15. Steatite powder with a relative density of 2.25 was bought from a local supplier. **Figure 1** shows the chemical parameters of steatite. Steatite was examined using XRD analysis to identify the chemical structural change and characteristic peaks confirm its crystalline structure, as depicted in **Figure 2**.

According to IS 383:2016.[53] specifications and grading zone II requirements, Crushed stone sand with a specific gravity of 2.65 was utilized. In addition, locally available, Coarse Aggregate with a nominal size of 20 mm and specific gravity of 2.7 was employed. In this investigation, potable water that complied with IS: 456:2021.[54] was used to mixing and curing process.

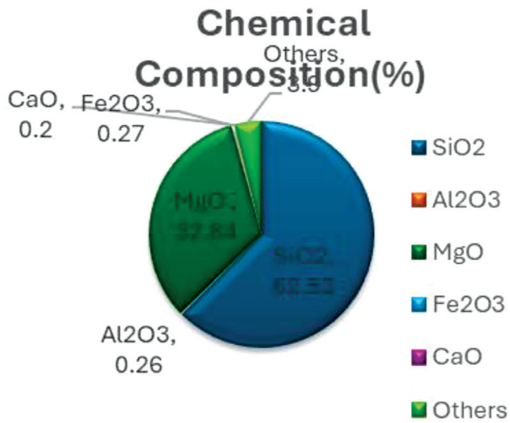

Figure 1: Chemical composition of SP

Workability was maintained by the inclusion of chemical admixtures like Conplast SP430.

2.1 Mix Design and Methodology

The current research investigated the concrete paste matrix by using steatite as an alternative to cement. In compliance with IS 10262–2019.[55] weighted averages were used for component proportioning in the preparation of M30-grade concrete. At 5 % intervals, steatite was substituted in varying amounts from 0 % to 15 % of the total weight of the cement. A constant water-to-cement ratio of 0.43 was employed in the mixing process for all concrete mixtures. **Table 1** provides an overview of the mixes that were developed. The reference mix was made up of 100 % OPC. Mix designations were given as S0 to S15, where "S" denotes steatite powder (SP). **Figure 3** depicts the flow chart of the methodology considered in this study. To know the workability of freshly mixed concrete a slump cone test was performed. A compressive, split tensile and flexural strength test was

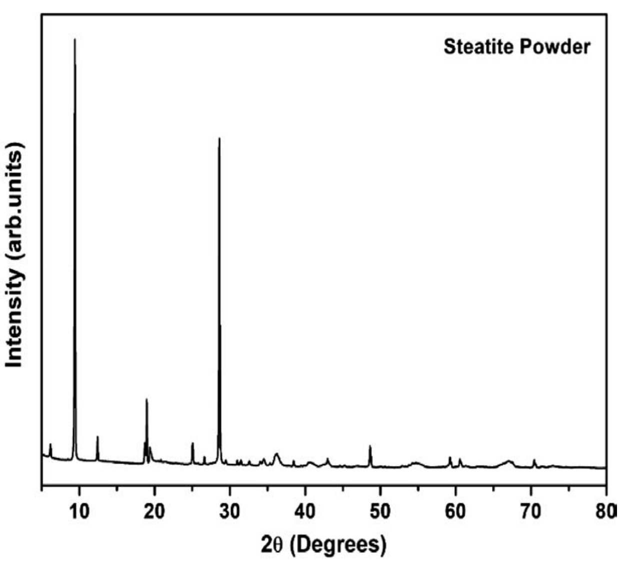

Figure 2: XRD image of Steatite Powder

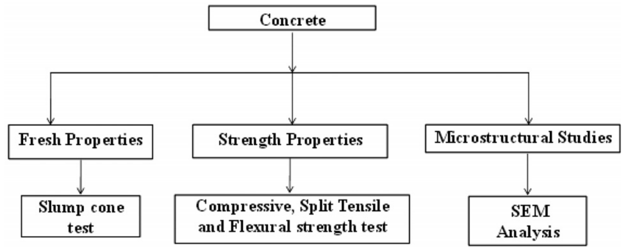

Figure 3: Flowchart representing the methodology

conducted to assess the hardened properties. Cube specimens of 150 mm × 150 mm × 150 mm were cast for compression testing as per IS 516:2021.[56] On the other hand, cylinder specimens measuring 150 mm in diameter and 300 mm in height were produced for split tensile testing according to IS 5816:1999.[57] A flexural strength test was made using beam size of (100 × 100 × 500) mm as per IS 516:2021.[56] These experiments were carried out for 7 days and 28 days of curing.

Table 1: Mix proportions designed for concrete

Mix designation (%)	Cement (kg/m^3)	SP (kg/m^3)	Crushed stone sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
S0	356.43	0	821.58	1109.62	153.264
S5	338.61	17.82	819.3	1106.54	153.264
S10	320.78	35.64	815.88	1101.92	153.264
S15	302.96	53.46	813.6	1098.85	153.264

3 RESULTS AND DISCUSSION

3.1 Fresh Properties

The workability of concrete was evaluated by slump cone test prior to casting. The fresh characteristics of concrete were shown in **Figure 4**. The slump value for 5 % inclusion of steatite exhibited 80 mm, which is more than normal concrete and it created good workability. For the replacement of 10 % and 15 % steatite to cement produced 78 mm and 72 mm slump values. As the steatite content increased, the size of particle impacted on

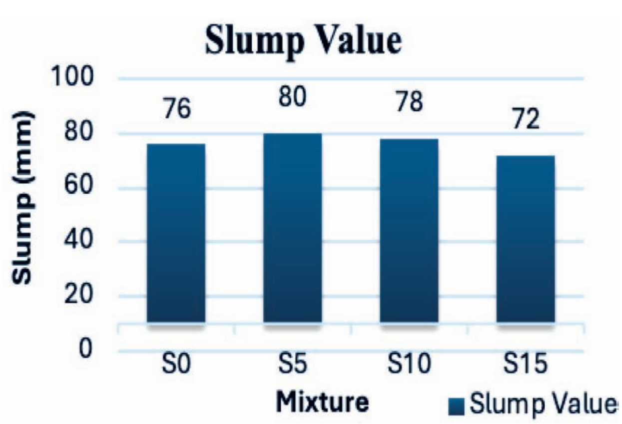

Figure 4: Slump values for fresh concrete

water absorption capacity and formation of MSH in the mix raised due to this condition the workability reduced. The water requirement increased mainly because of magnesium compound present in Ultrafine Natural Steatite Powder.[50] In self-compacting concrete the addition of SP and Viscosity Modifying Admixture (VMA) produced true slump, and it was pointed out as spread diameter of the slump value was reduced at higher percentage inclusion of steatite due to absorption of more water content in SP.[38]

3.2 Compressive strength

The compressive strength (CS) of the concrete mixture is depicted in **Figure 5**. The average of three samples was taken for each combination for curing periods of 7 d and 28 d. When 5 % steatite was substituted, the strength for 7 d and 28 d was 23.53 MPa and 36.2 MPa, respectively, which was 3 % greater compared to the regular concrete. Similarly, for 10 % and 15 % substitution, the strength values were 21.32 MPa and 32.8 MPa, and 20 MPa and 30.5 MPa, respectively. The magnesium silicate hydrate (MSH) and calcium silicate hydrate (CSH) gels were obtained during the hydration process in the mixture.[41] This boosted early-age strength by preserving the cohesiveness of the entire gel. A large amount of SiO_2 present in the steatite powder reacted with portlandite ($Ca(OH)_2$), producing additional C–S–H gel. The microparticles of steatite physically occupied capillary spaces in the concrete blend and helped to increase the particle packing density. Nevertheless, it improved the load-transferring capacity by reducing the interconnected porosity in the ITZ. The micropores were sealed with secondary hydration products, further densifying the matrix. Hence, this mechanism is beneficial in increasing the compressive strength of concrete. The strength value was shown to decline as the proportion of steatite increased, due to the reduced OPC content acting as a binding agent. As a result, the formation of CSH gel decreased, which is the primary product of hydration, and there was insufficient $Ca(OH)_2$ to complete the pozzolanic reaction. Therefore, the appropriate strength value was observed at 5 % steatite substitution.

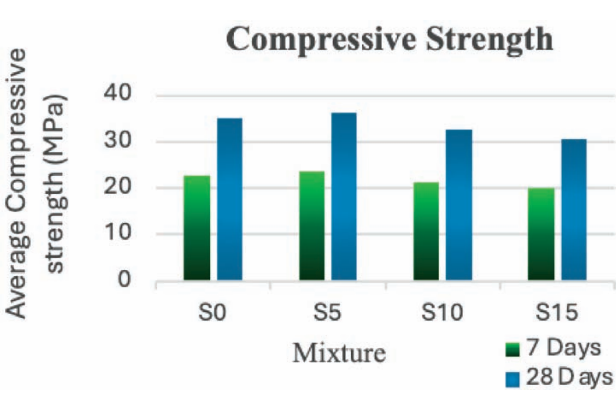

Figure 5: Compressive Strength of Concrete Mix

In self-compacting concrete, the use of fly ash with 15 % steatite generated better strength due to sufficient CSH and MSH gel formation. Similarly, adding polypropylene fibre by weight of concrete exhibited maximum strength.[39,44] The smaller particle size of steatite and the presence of magnesium in the concrete blend exhibited higher strength up to 20 % substitution.[45]

3.3 Split Tensile Strength

Figure 6 depicts the split tensile strength for the samples cured for 7 d and 28 d. The tensile strength of 3.15 MPa was developed for 5 % inclusion of steatite powder to the mix. In contrast to normal concrete, it reveals 3 % higher value. Likewise, 10 % and 15 % of the addition of steatite produced less strength such as 2.9 MPa and 2.5 MPa. Concrete's strength was discovered to have diminished when steatite was substituted more than 5 %. In the hydration process, the tiny particles of steatite blend with cement and generate MSH and CSH gel. This formation helps to enhance the split tensile strength of the mixture. Hence the incorporation of 5 % steatite is considered as the optimum mix combination with cement. In self-compacting concrete, the supplement of FA and steatite were gave the greatest enhancement in strength for curing of 90 days.[39] Similarly, 15 % substitution of steatite in the SCC gave good strength and followed the same trend to the compressive strength outcomes for all agings.[41]

3.4 Flexural Strength

Figure 7 illustrates the flexural strengths achieved in hardened concrete. The 4.24 MPa flexural strength was attained by 5 % replacement of steatite powder with cement, and it showed 2 % higher than the ordinary concrete. Likewise, 4.05 MPa and 4 MPa strength was observed with the 10 % and 15 % addition of steatite. The acquired flexural strength decreased as the steatite content raised due to the high magnesium content that was released through the hydration process. The utilization of

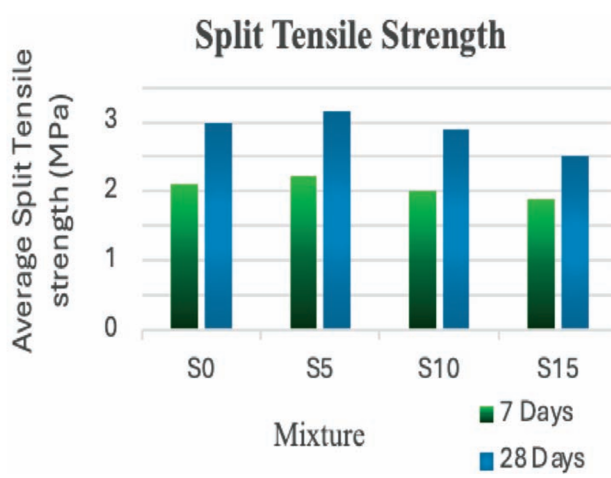

Figure 6: Split Tensile Strength of Concrete Mix

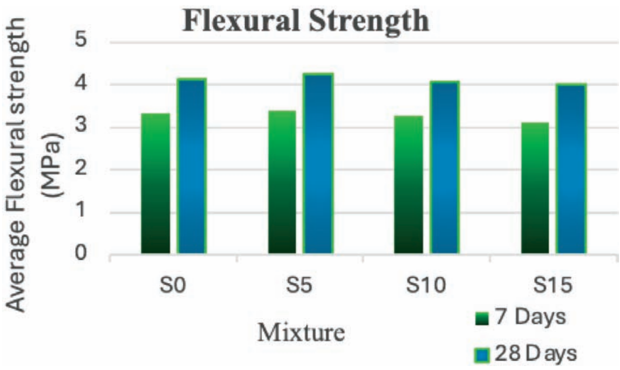

Figure 7: Flexural Strength of Concrete Mix

polypropylene fiber along with steatite in concrete led to the development of flexural strength over standard concrete.[44] As the steatite content rises in the mixture, the strength will start reducing because it converts into residual steatite that is no longer used as a filler. Thus, the strength began to decline.[39]

3.5 Microstructural Studies

Figure 8 depicts the microstructure study of the concrete specimen at 28 days using scanning electron microscopy (SEM). It is a highly adaptable technique and generates comprehensive surface information of samples and images with excellent resolution. This study reveals the detailed bond matrix and concrete morphology. The homogeneous and denser structure created with the help of CSH, MSH gel and excellent distribution of particles without agglomeration.[39] The pores present in the matrix were eliminated by fine particles of steatite and obtained gel indicators. Furthermore, it increases the hardness of the concrete by filling the gaps and enhanced the ITZ among mortar and aggregates.[47] Similar to this some special concrete also has improved ITZ.[58,59] The steady ettringite needle structure of the 5 % SP-based concrete was transformed into an irregular pattern by the continuous interaction of steatite, as appears in the images. Moreover, the matrix showed the complete encapsulation of aggregates, unreacted steatite particles, and an elevated microcrack density in ITZ. By minimizing the capillary pore connection and closing the gaps, this impact increases the strength and cohesiveness of the concrete paste. Consequently, the microstructure and bonding are strengthened when SP is added to concrete.

4 CONCLUSION

The purpose of this research was to explore the influence of steatite powder on the fresh, hardened and microstructural properties of concrete. These conclusions were reached after considering the investigation's outcomes:

- The good workability of 80-mm slump value was achieved with an addition of steatite powder. Nevertheless, as the proportion of steatite increased, it lowered the slump because the fine particles influenced the capacity of the mixture to absorb water and the production of MSH.
- The compressive strength of concrete was increased by 3 % reaching 36.2 MPa by employing 5 % SP over normal concrete. Furthermore, it dropped by 10 % and 15 % SP, since both of these blends include a higher concentration of magnesium.
- The 3.15 MPa strength was exhibited by split tensile test which was 5 % greater than the standard concrete and it is followed a similar trend to the compressive strength test outcomes.

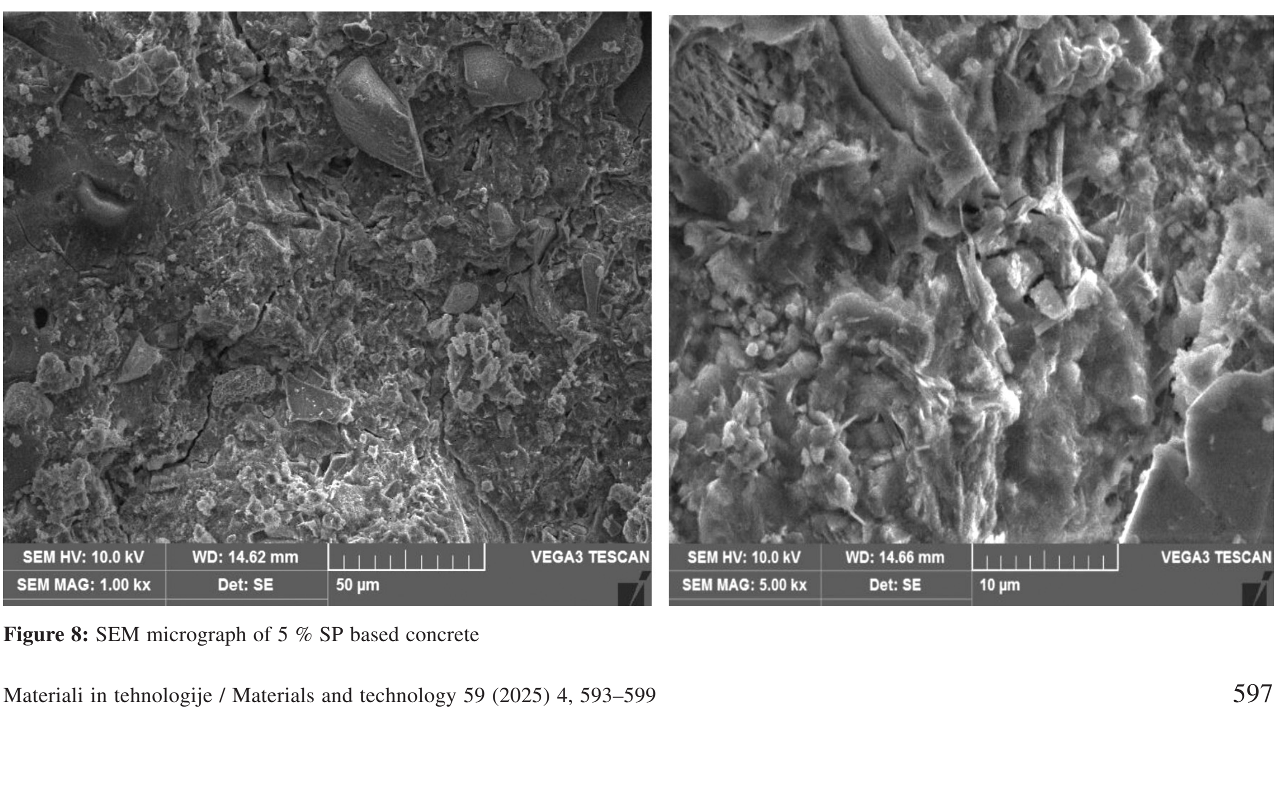

Figure 8: SEM micrograph of 5 % SP based concrete

- The 4.24 MPa flexural strength was attained by replacing 5 % of SP with cement, and it was 2 % better than conventional concrete.
- The ideal strength increase was found by adding 5 % steatite. This is because pores can be placed more easily when up to 5 % of steatite is present. Above this ratio, the strength declines since there are fewer spaces and the remaining steatite in the cement paste becomes inert.
- Based on the SEM analysis, it is revealed that fine particles of steatite raised the formation of CSH and MSH gel in the pozzolanic activity and improved the porosity as well as strength by sealing the microcracks.
- Since steatite powder mitigates the negative consequences of the cement-making process, including greenhouse gas emissions, it can be proposed that it is an appropriate choice for sustainable growth.

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