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PERFORMANCE EVALUATION AND MICROSTRUCTURAL ASSESSMENT OF ECO-FRIENDLY CONCRETE WITH MICRONIZED BIOMASS SILICA AND STEATITE POWDER

OVREDNOTENJE LASTNOSTI IN OCENA MIKROSTRUKTURE OKOLJU PRIJAZNEGA BETONA Z DODATKOMA IZ MIKRONIZIRANE SILIKATNE BIOMASE IN STEATITNEGA PRAHU

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Cement is the most widely used binder in concrete around the globe. Natural assets are utilised as raw materials to make the essential components used in the production of concrete. This process requires an enormous quantity of energy and emits greenhouse gases, especially carbon dioxide (CO_2), which contribute to global warming and have an adverse effect on the environment. These hazardous emissions produced by the cement industry can be minimized by employing alternate approaches, such as partially replacing cement with supplementary cementitious materials (SCMs). Many research investigations examined the effectiveness and performance of pozzolanic substances as an alternative to cement. In the present study, cement is partly replaced with different SCMs, such as micronized biomass silica (MBS) and steatite powder (SP). Various proportions of MBS – (3, 6, 9 and 12) % – were used. Furthermore, a consistent SP content of 5–10 % was utilised. Fresh, mechanical and microstructural features of concrete were studied after the inclusion of SP and MBS. The incorporation of 6 % MBS and 5 % SP generated an excellent compressive strength of 41 MPa, which was 17 % higher than that of ordinary concrete. Similarly, the split tensile and flexural strengths were 3.66 MPa and 4.5 MPa, respectively. It was observed that introducing these elements to cement enhanced its mechanical and microstructural properties. Thus, the optimal combination determined included 5 % SP and 6 % MBS. According to the scanning electron microscopy (SEM) study, the structure of the concrete matrix was improved by sealing the micropores and interfacial transition zone (ITZ) with the calcium silicate hydrate (CSH) and magnesium silicate hydrate (MSH) gels, resulting in a denser microstructure. These components demonstrated their ability to substitute cement without impairing the performance of concrete. Overall, MBS and SP are excellent supplementary cementitious materials. Thus, the results of this research have practical significance for potential application of these components in the production of sustainable concrete.

Keywords: steatite powder, micronized biomass silica, interfacial transition zone

Cement je na svetu najbolj pogosto vezivo, ki se uporablja za izdelavo betona. Za proizvodnjo betona se poleg tega uporabljajo še druge dragocene naravne surovine. Proizvodnja cementa zahteva tudi ogromne količine energije in proizvaja toplogredne pline, predvsem CO_2, ki prispeva k globalnemu segrevanju in tako ima negativni vpliv na okolje. Te nevarne izpuste toplogrednih plinov, ki jih proizvaja industrija cementa, je mogoče zmanjšati z alternativnimi pristopi, kot je naprimer delna zamenjava cementnega veziva z dodatnimi cementitnimi materiali (SCM; angl.: supplementary cementitious materials). Mnoge znanstvene raziskave so bile namenjene ugotavljanju učinkovitosti in sposobnosti pucolanske snovi (finozrnat vulkanski pepel) kot alternativa cementu. Ime »pucolanski« materiali so dobili po mestu Pozzuoli v Italiji, kjer so ga prvi odkriti in uporabili Rimljani. V tem članku pa avtorji opisujejo raziskavo v kateri so cement delno nadomestili z različnimi deleži SCM, kot sta biomasa mikronizirane silike (MBS; angl.: micronized biomass silica) in steatitni prah (SP). Uporabili so različne kombinacije deležev MBS (3%, 6%, 9% in 12%) in SP (od 5% do 10%). Nato so analizirali mehanske in strukturne lastnosti izdelanega betona v odvisnosti od vsebnosti izbranih dodatkov. Z dodatkom 6% MBS in 5% SP so dobili odličen cement s tlačno trdnostjo 41MPa, kar je za 17 % višja vrednost kot jo ima standardni beton. Podobno odlični sta bili tudi vrednosti za cepilno (3,66 MPa) in upogibno trdnost (4,5 MPa). Tako so avtorji raziskave dobili potrditev, da vpeljava teh dveh dodatkov k cementu izboljša mikrostrukturne in posledično mehanske lastnosti betona. Analize so pokazale, da je optimalna kombinacija dodatkov 5 % SP in 6 % MBS. Pregled in analiza strukture izdelanega betona pod vrstičnim elektronskim mikroskopom (SEM) sta pokazali, da je zaradi dodatkov prišlo do zapiranja mikropor in medfazne prehodne cone (ITZ; angl.: interfacial transition zone) s silikat-hidratnima geloma na osnovi Ca (CSH) in Mg (MSH). To je povzročilo nastanek gostejše mikrostrukture. Ta dva dodatka sta dokazala, da sta sposobna zamenjati del cementa, ne da bi pri tem prišlo do poslabšanja lastnosti betona. Skratka, MBS in SP sta odlična dodatna cementna materiala.Zato imajo rezultati te raziskave praktičen pomen za potencialno uporabo teh komponent pri proizvodnji trajnostnega okolju prijaznega betona.

Ključne besede: steatitni prah,mikroniziranana silikatna biomasa, medfazna prehodna cona

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1 INTRODUCTION

Concrete is a composite material made from renewable resources. It is employed around the world because of its flexibility and economic benefits.[1] A key ingredient in the production of concrete is cement and its demand is high due to rapid urban sprawl and infrastructural development.[2] As cement is the primary binding component of concrete, the construction industry has increased its production.[3] The manufacturing of cement causes considerable energy consumption, resource depletion and global climate change, as it emits significant amounts of CO_2 as well as other fluorinated gases.[4] Around 7 % of CO_2 is produced annually by the fabrication of ordinary Portland cement; every metric tonne of Portland cement clinker is proportional to around one metric tonne of CO_2, which affects the atmosphere. This environmental contamination can be reduced by including a substitute element instead of cement.[5] Three quarters of the world's energy consumption and 40 % of its greenhouse gas emissions are due to the fabrication activity.[6] For the development of infrastructure, it is necessary to provide environmentally friendly and economically feasible construction materials,[7] limiting the emissions of greenhouse gases while improving the infrastructure.[8] For the long-term progress of the cement industry, while achieving sustainability goals and conserving earth's resources, some important parameters must be considered such as reducing the clinker-to-cement ratio, applying novel technologies like carbon capture and using other supplementary cementitious compounds.[9]

The process of making green concrete incorporates a variety of residues and byproducts which otherwise end up in landfills, but can be used as alternative cementitious elements.[10] These can be developed from natural pozzolans, dust, powders, ashes, natural minerals, industrial and agricultural byproducts such as fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), silica fume, metakaolin, marble powder, glass powder, limestone powder, palm oil fuel ash, eggshell powder, volcanic pumice powder, ceramic waste powder (CWP), biomass fly ash, etc. SCMs have the potential to lower concrete's carbon footprint.[11,12] The inclusion of SCMs in the materials composed of cement influences its characteristics, notably its chemical reaction, formation of strength, microstructure and durability.[13] All these byproducts are utilised in different types of concrete such as ultra-high-performance concrete, high strength concrete, mass concrete, self-compacting concrete (SCC), geopolymer concrete (GPC), etc.[14,15] The strength properties are enhanced by adding waste biomass ash and silica sand, substituting up to 10 % of cement. Concrete with partial cement replacement could be suitable for low-strength precast elements.[16] A 15 % amount of textile effluent sludge in concrete can allow for the most effective fresh, mechanical, and non-destructive outcomes.[17] According to the results, the use of ESP and agricultural waste from date palm trees acting as binder ingredients greatly decrease the cost and CO_2 emissions while improving the concrete's performance.[18]

There have been numerous studies on the effectiveness of ordinary concrete that contains an agricultural byproduct such as RHA, but limited research has been done on concrete that incorporates MBS. Rice husk is burned under controlled conditions at 500–600 °C in a rotating kiln to produce MBS. The husk is then crushed in a jar mill for several hours to minimize the particle size. This process is called micronization; and since the silica content is significantly higher than that of RHA, the product is referred to as micronized biomass silica.[19–22] MBS accounts for 20 % of the 590 million tonnes of paddy produced globally. In addition, CSH gel is formed as a result of silica's interaction with hydration products. This enhances the durability and strength of concrete.[23] The performance of the ready-mix geopolymer is enhanced when up to 20 % of MBS is replaced with GGBS.[24] All curing ages show the greatest strength metrics at 25 % blending, including nano-biomass silica, polycarboxylate ether, and a bio-admixture.[25] It was determined that the geopolymer concrete mix with 20 % MBS and the remaining proportion of GGBS as the binder exhibit the best performance in terms of strength and durability.[26] According to the findings, the strength of concrete increases with MBS up to a certain level, after which it declines and is further strengthened by fibres. The perfect blend for concrete is achieved with a 10 % MBS content and a 0.2 % fibre addition.[27] It was established that specimens containing 20 mL of bacteria and 8 % MBS give the most effective results.[28] The utilization of 10 % MBS combined with construction and demolition waste provided greater compressive, split-tensile, and flexural strength.[29] After 28 d of curing, tests demonstrated that concrete containing 12 % MBS and 100 % recycled aggregate (RA) may reduce water permeability and increase compressive strength up to a certain level.[30] It is feasible to replace cement with about 20 % MBS without affecting its performance, and a 10 % replacement results in good strength.[31] The identified ideal percentage is 12 % MBS, which allows excellent concrete performance in terms of water permeability and compressive strength.[32]

Steatite powder is a metamorphic material with a high talc content, which gives it a great degree of versatility and consists mainly of hydrated magnesium silicate. SP is also known as soapstone.[33] According to the United Nations Framework Classification for Resources as of 2010, steatite reserves and resources are estimated to be 269 million tonnes, of which a substantial amount (22 %) is available in Karnataka.[34] SP is used in different industries, producing paints, ceramics, pottery and polymers.[35] Various researchers found that steatite powder has a stable crystal structure and high chemical resistance; hence, it can be potentially employed as an SCM and used for special concrete, including self-compacting concrete, geopolymer concrete and self-healing concrete.[36,37] Cement can be replaced by two materials, namely FA and up to 30 % SP, which provide for a higher strength compared to the reference concrete.[38] When the amount of ultrafine natural steatite powder (UFNSP) is increased, the water requirement is also higher and workability is reduced; however, the effective strength gain in concrete is achieved at the steatite optimum dose of 15 %.[39] Similarly, greater strength is observed with additions of 40 % GGBS and 10 % UFNSP.[40] According to research, the addition of 15 % UFNSP results in peak strength and mechanical properties remain high up to 20 % UFNSP due to its fine particle size. In SCC and self-healing concrete, the inclusion of 15 % steatite powder achieves the optimum value.[41]

The incorporation of SP results in a rigid structure and strengthens alkali-activated UFNSP-based geopolymer mortar.[42] Cement can be replaced with 15 % SP and polypropylene fibre, which produce good results.[43] An SEM study reveals that the mapping of silicate and magnesium shows uniform surface dispersion and the formation of magnesium silicate hydrate gels, which improve the strength and durability and contribute to the development of denser forms.[44] The amounts of pores in concrete are reduced and the microstructure of geopolymer concrete is improved using SP.[45] The formation of CSH and MSH is observed with SEM. When specimens are treated with UFNSP, their microstructure density increases, leading to enhanced strength and decreased gaps in the concrete structure.[46] A recent study showed that utilization of metasteatite, a thermally processed form of steatite, results in the formation of magnesium silicate-rich compound and improved particle packing, leading to a dense and continuous microstructure. The 10 % metasteatite improves the magnesium oxychloride cement paste, exhibiting its effectiveness in enhancing resilience to water.[47] With 10–25 wt.% metasteatite, each mixture shows a significant improvement in the strength after 14 d and 28 d, along with a noticeable trend toward a longer hydration time.[48] The above makes it apparent that there are numerous studies on MBS with different supplementary cementitious substances and SP with other sustainable materials in the scientific literature. However, the research gap, or the grey area, is the mixture of MBS and SP, as there are no studies discussing this combination. To ensure environmental sustainability, concrete should provide both strengths and benefits to the ecology and economy. Therefore, the purpose of this research is to evaluate the fresh, mechanical and microstructural characteristics of cement concrete that contains MBS and SP. It is anticipated that the use of MBS and SP will result in the creation of environmentally conscious infrastructures.

2 EXPERIMENTAL INVESTIGATION

2.1 Material

Ordinary Portland cement (OPC) of grade 53, which complies with IS 12269:2013, a cementitious compound with a specific gravity 3.15, was used to make concrete mixes. For the fine aggregate (FAG), crushed stone sand with a specific gravity of 2.65 was selected in accordance with IS 383:2016 and grading zone II standards. Furthermore, a coarse aggregate (CAG) having a specific gravity of 2.7 and a nominal diameter of 20 mm, that was easily accessible, was utilized. Potable water that complied with IS: 456:2021 was employed in this experiment for the purpose of mixing and curing. Conplast SP430, a chemical admixture, was added to maintain workability. The SCM employed in the investigation included MBS and SP. The grey MBS and white SP with specific gravities of 2.28 and 2.25 had been procured from a local supplier. **Figure 1** depicts the SP and MBS. Chemical characteristics of the MBS and SP are listed in **Table 1.**

Figure 1: Steatite powder and micronized biomass silica

Table 1: Chemical compositions of MBS and SP

Chemical composition	MBS (%)	SP (%)
SiO_2	95.561	62.566
Al_2O_3	–	3.005
Fe_2O_3	0.164	2.51
CaO	0.797	1.42
MgO	–	30
K_2O	1.982	–
SO_3	0.25	0.12
TiO_2	–	0.22
Cl	0.314	–
P_2O_5	0.805	–

2.2 Mix proportions and methodology

In accordance with IS 10262:2019, the processes for obtaining the necessary components for standard concrete were carried out. This study created an M30 concrete mix by substituting cement with supplementary binders MBS and SP. **Figure 2** displays the methodology flow chart. In the cement, the amounts of SP were maintained at 5 % and 10 %, while the MBS proportions varied from 0 % to 12 % in an interval of 3 %. Among a reference blend, four mixtures without SP, five mixtures with 5 % SP, and five mixtures with 10 % SP were prepared, resulting in a total of 15 mix combinations. All mixes had a water-cement ratio of 0.43 and contained 1 % superplasticizer by weight of the cement. Precise mix designs are listed in **Table 2**.

For the mixes, raw ingredients such as cement, MBS, SP, fine and coarse aggregates were weighed and blended in dry conditions, then mixed with water and superplasticizer. The workability of the new concrete mixes was evaluated using a (100 × 200 × 300) mm slump cone in compliance with IS 1199:2018 before the specimens were cast in moulds. To assess the hardened, the specimens were demoulded after 24 h, kept for curing in a curing tank, and then they were examined after 7 d and 28 d. To determine the compressive strength, a

Table 2: Mix proportions (kg/m^3)

Mix ID	Cement	MBS	SP	FAG	CAG	Water	Superplasticizer
M0S0	356.43	0	0	821.58	1109.62	153.264	3.56
M3S0	345.73	10.69	0	821.58	1109.62	153.264	3.56
M6S0	335.04	21.38	0	819.3	1106.54	153.264	3.56
M9S0	324.35	32.08	0	819.3	1106.54	153.264	3.56
M12S0	313.66	42.77	0	819.3	1106.54	153.264	3.56
M0S5	338.61	0	17.82	819.3	1106.54	153.264	3.56
M3S5	327.92	10.69	17.82	818.16	1105.002	153.264	3.56
M6S5	317.22	21.38	17.82	817.02	1103.46	153.264	3.56
M9S5	306.53	32.08	17.82	817.02	1103.46	153.264	3.56
M12S5	295.84	42.77	17.82	815.88	1101.92	153.264	3.56
M0S10	320.78	0	35.64	815.88	1101.92	153.264	3.56
M3S10	310.09	10.69	35.64	815.88	1101.92	153.264	3.56
M6S10	299.4	21.38	35.64	814.74	1100.38	153.264	3.56
M9S10	288.7	32.08	35.64	813.6	1098.84	153.264	3.56
M12S10	278.02	42.77	35.64	813.6	1098.84	153.264	3.56

Note: M = micronized biomass silica (MBS) and S = steatite powder (SP)

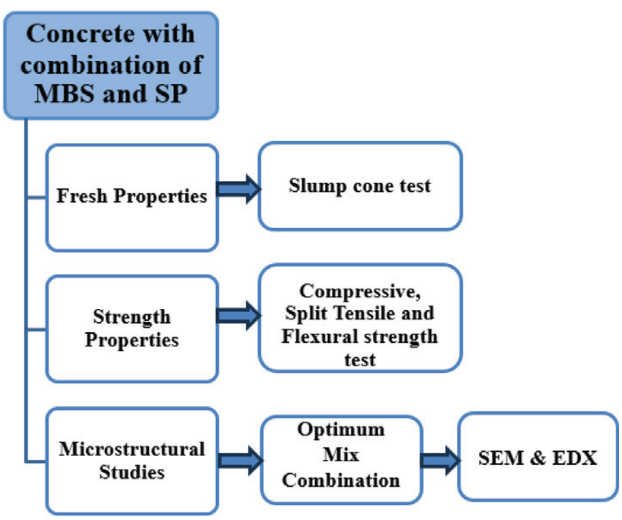

Figure 2: Methodology flow chart

Figure 3: Testing of compressive strength and split tensile strength

150 mm cube was constructed as per IS 516:2018. Similarly, for the split tensile strength test, cylindrical specimens measuring 150 mm in diameter and 300 mm in height were utilized in accordance with IS 5816:2004. **Figure 3** shows the testing of compressive strength and split tensile strength. The flexural strength test was conducted using a beam with dimensions of (100 × 100 × 500) mm as per IS 516:2018.

3 RESULTS AND DISCUSSION

3.1 Fresh properties

Concrete's fresh characteristics were examined using the slump cone test, as described in IS 1199:2018. Slump values for mixtures M3S5 and M3S10 were found to be 78 mm and 75 mm, indicating a minor effect on workability. Moderate workability was indicated for M6S5 and M6S10, when the slump values decreased to 75 mm and 73 mm. Furthermore, M9S5, M12S5, M9S10, and M12S10 showed a notable decrease in workability with slump values of (70, 68, 69 and 65) mm, respectively. A medium slump was observed for the optimum mixture. The slump values for different mix compositions are displayed in **Figure 4**. The results show that when the MBS and SP content increased, the slump values gradually decreased because the concrete mixture absorbed more water.[27,37] The presence of finer MBS and SP particles could potentially explain this observation. The high specific areas of MBS and SP are one of the reasons for not achieving high workability, but the addition of superplasticizer helped them achieve the medium slump. Increased contents of MBS and SP appear to contribute to the rigidity of the mixtures.[22] The cellular structure of MBS increases the absorption capacity of concrete, reducing the amount of water available for workability.[30,31]

3.2 Compressive strength

The strength of the cement concrete, which combines MBS and SP as the substitutes, was examined using a compression testing machine. The specimens that were evaluated for compressive strength are represented in **Figure 5**. Each strength result is the average of three specimens that were tested after 7 d and 28 d. Once the cement replacement including only MBS continues to increase, the strength of the concrete mixture grows as well up to a certain point. Similarly, when both MBS and SP mix combinations rise, the strength value also increases to a certain level compared to the control concrete. In comparison to all other mixtures, mix M6S5 provided an excellent strength of 41 MPa, which is 17 % higher than that of the control concrete. However, the strength of M12S10 is 12 % lower than that of ordinary concrete, with an exceptionally low strength of 31.2 MPa. When cement is partially replaced with 5 % SP along with (3, 6, 9 and 12) % MBS, the compressive strength values are higher than that of ordinary concrete. However, the results are less favourable when 10 % SP is incorporated together with the same percentage of MBS.

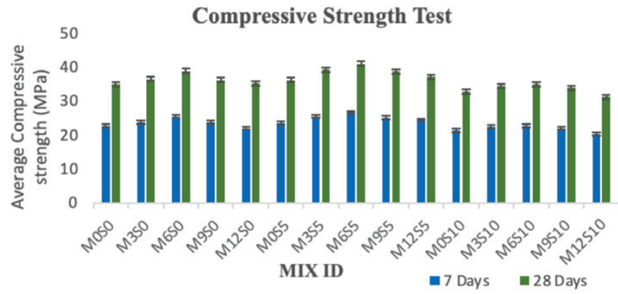

Figure 5: Compressive strength of concrete with various mix combinations

Based on the present work, the inclusions of 6 % MBS and 5 % SP gave the optimum result. The main cause for the strength improvement was the bonding between the cement paste and aggregate. Due to fine particles of MBS and SP, the cement binder became more effective and concentrated. The CSH from MBS and the MSH gel from SP were generated during concrete hydration. This minimised the weakest zone between the paste and aggregate called ITZ, and diminished the large space in the matrix. The development of the concrete's strength highly improved due to this mechanism. It was observed that as the formation of CSH and MSH gel from pozzolanic action decreased, the filling of micropores and ITZ was reduced and the compressive strength also decreased due to a higher level of inclusions of MBS and SP. Based on the research, the ideal replacement percentage for MBS and GGBS was 20 % of the total weight, which also positively affected the compressive strength of the material.[23] Because of MBS, the presence of more CSH gel and primary alumina silicate gel helped the geopolymer reach a higher strength.[26] It was shown that the compressive strength increased with up to 8 % of MBS and 20 mL of bacterial solution after MBS was incorporated, partially replacing cement. MBS performs as a pozzolanic material in the process of hydration and as a filler increasing the density of microsystems.[28] Similarly, the strength the RA concrete incorporating MBS was enhanced, indicating that long-term strength improvements are facilitated by MBS.[30] The inclusion of SP and other supplementary cementitious materials like FA, GGBS and fibres leads to the formation

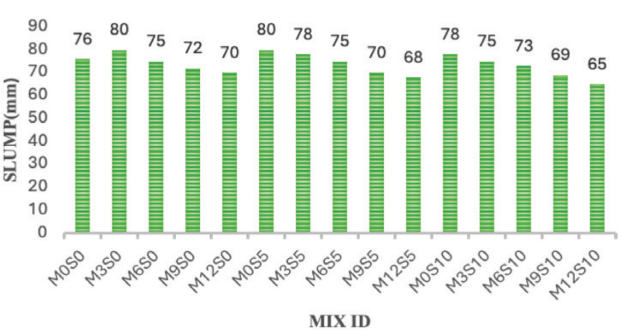

Figure 4: Slump values for different mix compositions

of MSH and CSH gels, resulting in a significant improvement in the strength of concrete, SCC and GPC[37,39,43]

3.3 Split Tensile strength

The split tensile strength of concrete with different mix proportions cured for 7 and 28 days is illustrated in **Figure 6**. Based on the studies, it was found that the split tensile strength of the M3S5, M6S5, M9S5, and M12S5 concrete was (17, 23, 13 and 11) % higher compared to the control concrete. Likewise, the split tensile strength of M3S10, M6S10, M9S10, and M12S10 was (12, 15, 11 and 9) % higher than that of the regular concrete. Excellent strength was achieved by the M6S5 combination, i.e., 3.66 MPa after 28 d, which was 23 % higher than that of the reference concrete. The primary cause of this strength increase was the fine MBS and SP particles. By reacting with cement hydrates during the pozzolanic reaction, these substances created secondary CSH and MSH gels in the mixture, strengthening the compositional bond, lowering the ITZ, minimising the microcracks, and improving the split tensile strength. Nevertheless, as the proportion of MBS and SP in the mixture increased, these substances affected the workability of concrete by reducing its water content and decreasing its split tensile strength. The hydration mechanism was improved due to the SiO_2 concentration in the MBS, which was above 80 %; thus, the strength increased with 8 % MBS and 20 mL of bacterial replacement.[28] The results indicated that when 15 % SP and 10 % FA were incorporated into a special type of concrete, like SCC, the tensile strength increased by up to 19 %.[39] In a similar way, adding 0.5 % of polypropylene fibres and 15 % of the steatite powder to cement resulted in a maximum strength value of 3.9 MPa after 28 d.[43]

3.4 Flexural strength

The flexural strength of the concrete mixtures is shown in **Figure 7**. According to the research, the flexural strengths of the M3S5, M6S5, M9S5, and M12S5 concrete were (6, 9, 5 and 4) % higher than that of ordinary concrete. It should be noted that 6 % MBS and 5 % SP provided the best results, with a strength of 4.5 MPa after 28 d. Meanwhile, the flexural strength declined with an increase in the MBS & SP proportion. The strength was enhanced with the incorporation of MBS & SP and the increased hydration effect. The packing capacity of concrete also increased. However, the spherical particles of MBS caused inadequate bonding amongst other concrete ingredients, therefore the flexural strength diminished above 8 % of MBS.[28] When SP and polypropylene fibre were added to concrete, the flexural strength increased by 31 % compared to ordinary concrete.[43] It was demonstrated that integrating MBS to the concrete mix, combined with treated RA improved the flexural strength.[22]

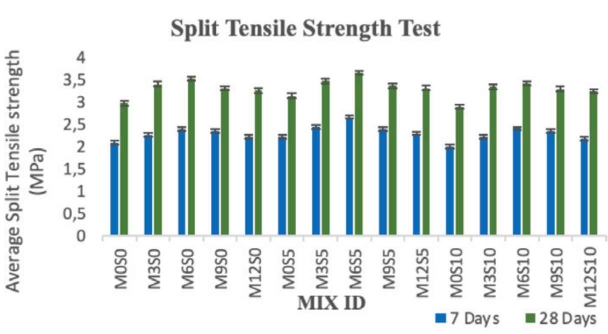

Figure 6: Split tensile strength of concrete with different mix proportions

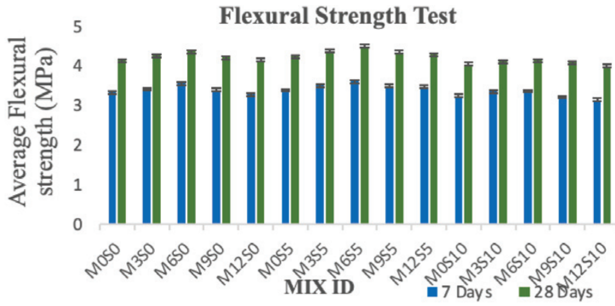

Figure 7: Flexural strength of the concrete mixtures

3.5 Microstructural studies

The microstructural investigation of the concrete was carried out using SEM. In this research, SEM images were generated to find optimal mix combinations such as M6S5. **Figure 8** depicts a SEM visualization of the M6S5 mixture. The formation of a thick gel-like structure can be observed in the images. During the hydration process in the mixture, silica and alumina react with $Ca(OH)_2$ and $Mg(OH)_2$ and generate essential hydration products like ettringite, CSH and MSH gels. These products enhance the strength. Ettringite is a substance created when tricalcium aluminate (C_3A) interacts with gypsum to form needle-like structures that enhance early strength. When MBS and SP are incorporated into concrete, their unique qualities, especially their large surface areas and small particles, improve the pozzolanic activity. The image depicts a dense, compact matrix with small apparent pore spaces, suggesting reduced porosity, improved mechanical interlocking and adequate particle packing, which are advantageous for the strength increase. A strong physical connection between the binder and reactive silica or magnesium-based phases is indicated by the rough and uneven surface appearance. The image shows a relatively crack-free matrix, implying a better stress distribution and reduced risk of crack propagation. The fine particle size of MBS and SP allows them to act as microfillers, enhancing particle packing and the cohesion of the microstructure with embedded hydration products, while minimizing permeability.

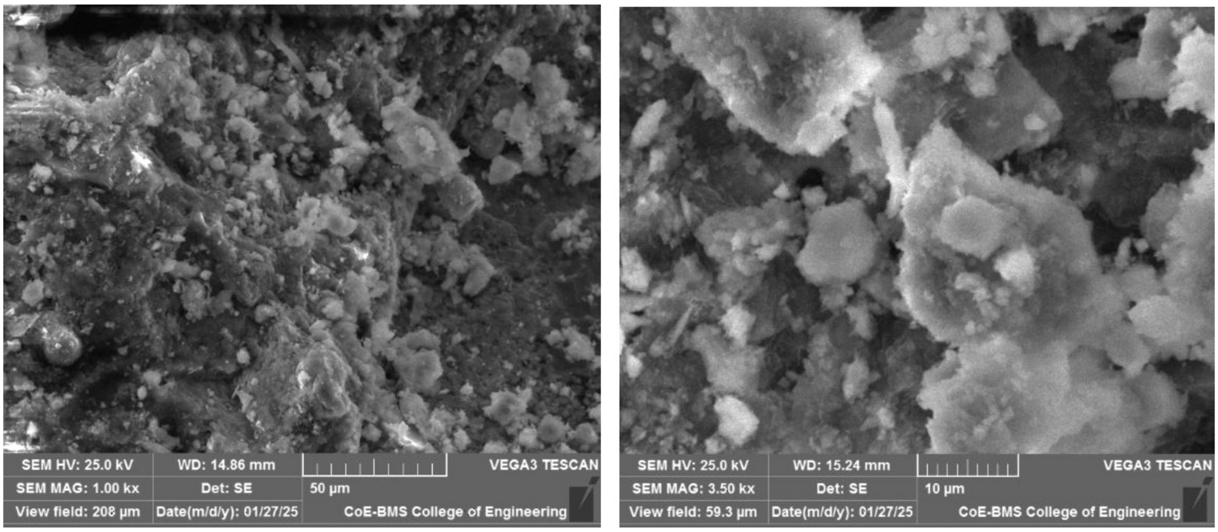

Figure 8: SEM image of M6S5 mix combination

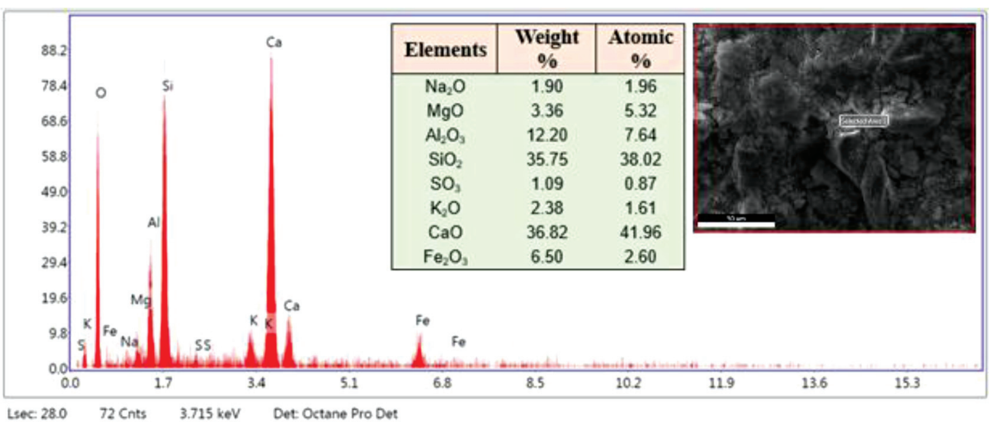

Figure 9: SEM-EDS image of M6S5 mix combination

The concrete with an 8 % MBS inclusion has a dense, solid surface whose ITZ is difficult to identify, as demonstrated by the SEM analysis. MBS makes it possible to fill in the ITZ, which results in dense concrete.[32] Strength and durability are improved due to the development of CSH gel and MSH, as evidenced by the complete filling of the microcracks and a substantially denser morphology of the SCC utilizing SP and FA.[39,44]

Another study found that using up to 15 % UFNSP would improve the strength and create a denser microstructural bond.[46] Steatite (primarily magnesium silicate) may contribute to the formation of MSH, which also adds strength and enhances durability. Therefore, it is noticeable from the microstructural analysis that the combined use of MBS and SP significantly enhanced the strength and pore structure. The SEM–EDS study was carried out on M6S5, the ideal mixture of blended concrete, as illustrated in **Figure 9**, to acquire a complete understanding of the concrete specimen's chemical structure. The EDX spectrum reveals high contents of SiO_2 and CaO, indicating strong potential for CSH gel formation, the key contributor to the concrete's strength. Moderate amounts of Al_2O_3 and Fe_2O_3 suggest potential formation of secondary hydration products such as C-A-H and C-F-H, contributing to the matrix densification. The presence of MgO from steatite could lead to the formation of the MSH gel, adding additional binding capacity. Minor oxides such as K_2O, Na_2O, and SO_3 may influence the setting behaviour and early-age strength. According to the analysis, CaO and SiO_2 are the main oxides in the modified concrete matrix and are necessary for the development of CSH gels that are strong.

Enhancing structural connectivity and densification, the addition of MgO and Al_2O_3 permits the creation of additional gel phases, such as MSH and C-A-H. This is supported by the SEM micrograph, which displays a dense microstructure with well-distributed hydration products and decreased porosity. These microstructural changes contribute to the significant improvement in mechanical features. The amounts of CSH in the mixes are impacted by pozzolanic processes over time. A drop in the atomic calcium-to-silicon (Ca/Si) ratio indicated that the majority of the cements reacted with portlandite (CH).[49] The denser structures were often developed when there was a decline in the Ca/Si ratio and a rise in the rate of CSH formation.[50] A similar trend of improved bonding and a better microstructure was observed in various types of concrete when adding a mineral admixture and supplementary cementitious materials.[51,52] Furthermore, the pozzolanic characteristic of the MBS blends with calcium hydroxide enhancing the microstructure gradually, results in a composite that is not only strong but also environmentally sustainable.

4 CONCLUSION

The present research intended to examine the performance of concrete when natural and agricultural byproducts like steatite powder and MBS were included as supplemental cementitious substances to support sustainable building practices. According to the mechanical and microstructural investigations, the following key conclusions are drawn:

- In comparison to all other concrete blends, the M3S5, M3S10, and M6S5 combinations had the highest slump values, exhibiting excellent workability as well as improved compacting capacity. When the MBS and SP levels increased, the concrete mixture absorbed more water, resulting in the slump values to gradually decline and the workability to significantly deteriorate.
- The M6S5 mixture exhibited an exceptional compressive strength of 41 MPa, which was 17 % higher than that of the conventional concrete, in contrast to all other combinations. The application of SP and MBS contributed to the enhanced strength since their fine particles enable them to develop a dense structure.
- The incorporation of 5 % SP and 6 % MBS allowed for a high splitting tensile strength, 3.66 MPa after 28 d, which was 23 % higher than that of the standard concrete.
- The concrete with 6 % MBS and 5 % SP exhibited the highest flexural strength of 4.5 MPa after 28 d, which can be attributed to the enhanced hydration activity and finer particle size.
- The SEM and EDS investigation revealed a dense microstructure and strong bonding in the ITZ, owing to the presence of SP and MBS, as well as a significant formation of CSH and MSH.
- Strength parameters declined with an increase in the MBS and SP percentage due to the reduction in the CSH and MSH gel formation in the mixture.
- The inclusion of SP and MBS in the concrete increased its strength. The optimal amounts of SP and MBS substituting cement were 5 % and 6 %, respectively.
- Utilizing SP and MBS leads to more economical and sustainable materials. This method has the potential to reduce CO_2 emissions by partially replacing cement.

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