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Magnesite mine waste as a sustainable binder for low-fines self-compacting concrete: engineering property and ecological impact

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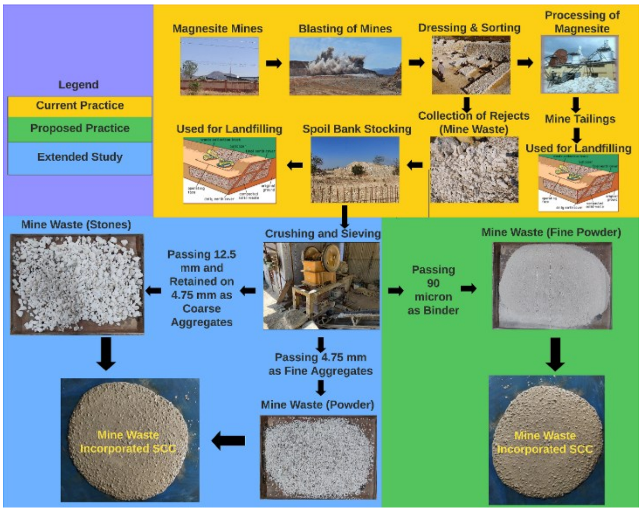
Graphical abstract



Abstract

Mine waste management has become a global concern due to its environmental and health impacts, as well as the high cost of disposal. Recent advancements focus on recycling mine waste into resources using effective conservation methods and waste management systems. The building sector, a major consumer of natural resources, has seen studies on using waste materials in concrete. This study examined the feasibility of replacing cement with mine waste in two phases - binary blend (cement + mine waste) and ternary blend (cement + fly ash + mine waste) at 10%, 20%, and 30% doses. The study evaluated fresh properties like slump flow, T50 slump, V-funnel, J-ring, and L-box, and hardened properties like compressive, splitting tensile, and flexural strengths. It also investigated microstructural characteristics, cost, energy impact, and CO_2 emissions. The results showed good performance in fresh characteristics for almost all mixtures but failure in hardened properties. The achieved strength was backed by microstructural analysis. Binary blended SCC reduced costs by 5%, energy by 25%, and CO_2 emissions by 28%, while ternary blended SCC cut costs by 8%, energy by 32%, and CO_2 emissions by 36%.

Keywords: SCC; magnesite mine waste; fresh and hardened properties; sem analysis; cost analysis; co₂ emission analysis; energy analysis

1. Introduction

1.1. Need for Alternate Binder

The demand for Portland cement has become increasingly intense in modern years due to the growing need to extend the built environment within cities. Approximately 4.1 Gt of cement was produced worldwide in 2019; by 2030, production will reach 4.83 Gt per year (Miller *et al*. 2018). However, the adverse effects of cement manufacturing primarily attract environmental organizations' attention to this problem. The decarbonization of limestone alone produces around 60% of the CO_2 emissions. This leads to several issues, including natural resource depletion and rising greenhouse gas (GHG) emissions globally, which exacerbate environmental pollution, contribute to climate change, and pose health hazards to people (Scrivener *et al*. 2018). Since several business segments have been working to lower energy use and CO_2 emissions, the building sector must also begin to think more about sustainability. Therefore, to address these environmental challenges, it is imperative that cement usage be drastically reduced and alternative materials are looked after to replace conventional ones (Yu *et al*. 2015). Replacing cement components with alternative materials is the most assuring strategy to reduce greenhouse gas emissions. For instance, substituting supplementary cementitious materials (SCMs) for the majority of cement reduces the need for clinker production (Habert *et al*. 2020). The use of SCMs is significant because it can minimize GHG emissions and inappropriate use of non-renewable materials in cement production by roughly one billion tons annually if 50% of the clinker used in concrete production is replaced (Celik *et al*. 2014). SCMs are particularly helpful for self-compacting concretes (SCC) because they function as viscosity modifiers in a fluid state (Saleh Ahari *et al*. 2015). The SCMs derived from industrial by-products like fly ash, slag, metakaolin, glass, iron, rubber wastes, etc., are used in this perspective

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(Raveendran and K 2024). Since these materials are environmentally friendly and sustainable, they are likely to be used as raw materials to produce concrete, which will reduce the amount of cement needed and enhance the material's performance while also significantly lowering its carbon footprint (Diniz *et al*. 2022; Jain *et al*. 2022). Concrete sustainability is defined in a way that goes beyond the correlation between the amount of cement or binder and its compressive strength. Benefits such as waste integration into concrete, improvements in durability from the large amounts of mineral additives employed, and, most importantly, using Portland cement in fewer amounts than those used presently must all be taken into account (Anjos *et al*. 2020). Some wastes from industrial and agro-industrial sectors used as construction materials are tabulated below in Table 1.

Table 1. Previous studies on wastes as construction materials

Material	Waste type	Potential application in construction	Maximum Replacement	Effect on		Reference
				Workability	Strength	
Fly ash	Industrial	Binder	100%	+	+/-	(Ammasi *et al*. 2017; Nayak *et al*. 2022)
		Blended binder	75%	+	+/-	
Bottom ash	Industrial	Blended binder	45%	-	+	(Fediuk *et al*. 2023; Silva *et al*. 2023)
		Aggregate	20%	+/-	-	
RHA	Agro-waste	Blended binder	50%	+/-	+	(Diniz *et al*. 2022; Kannur and Chore 2023a)
Bagasse ash	Agro-waste	Blended binder	30%	-/+	+/-	(Diniz *et al*. 2022; Kirthiga and Elavenil 2023)
Waste glass	Industrial	Blended binder	40%	+	+	(Manikandan and Vasugi 2021, 2023; P and V 2022)
Sewage sludge	Industrial	Blended binder	15%	-	-	(Thukkaram and Kumar 2021; Shunmuga Vembu and Ammasi 2022)
		Aggregate	20%	-	+/-	
GGBS	Industrial	Binder	100%	+/-	-	(Tüfekçi and Çakır 2017; Manikandan and Vasugi 2021; Manikandan *et al*. 2022)
		Blended binder	60%	+/-	-	
Slag/Jarosite	Industrial	Blended binder	50%	+	-	(Nuruzzaman *et al*. 2023; Pandiyan and Solaiyan 2024b, 2024a)
Mine waste/tailings	Industrial	Blended binder	30%	-	+/-	(Medeiros *et al*. 2021; Zhang *et al*. 2023)
		Aggregate	80%	-	+/-	
Ceramic waste	Industrial	Blended binder	40%	-	+/-	(Gautam *et al*. 2022)

RHA – Rice husk ash, GGBS – Ground granulated blast furnace slag, "+" - Improvement, "- "- Decrement, "+/- "- Improvement and Decrement (improvement higher), "-/+" - Improvement and Decrement (decrement higher)

1.2. Mine waste and its ecological problems

The ability to build infrastructure to fulfil the demands of the present without sacrificing the needs of future generations is known as sustainability (Ministry of Planning and Statistics Authority 2018). Currently, mining is viewed to be vital to the socioeconomic development of countries possessing mineral resources. For instance, mining accounts for about 2.5% of India's GDP (Gross Domestic Product) (Chief Inspector of Mines and Head of the Directorate General of Mines Safety 2020). In a way, mining greatly degrades the environment, adversely affecting the Sustainable Development Goals (SDGs 10, 13 and 15); on the other hand, it generates employment and provides the raw materials required for economic expansion, enhancing SDGs-1, 2, 8, and 9 related to infrastructure and economy (Monteiro *et al*. 2019; Arendt *et al*. 2022).

1.3. Benefits of reusing mine waste

Literature study reveals several industrial wastes (solid waste), including mining wastes, have been effectively utilized in concrete production, especially as alternate binders. Esmaeili and Aslani (2019) utilized copper mine tailing instead of cement in concrete, and proved that the mechanical properties are improved compared to reference concrete, even when the cement substitution reached up to 30% (Esmaeili and Aslani 2019).

1.4. Magnesite mine waste and its benefits

Magnesite is one of the main ingredients used in refractory material production. Mining magnesite generates huge waste as mineral extracts are produced only from 7% of the mined ores; the remaining ores are deemed as trash/wastes (Indian bureau of mines 2020). These magnesite mine waste (MGW) rocks are landfilled openly since these enormously generated wastes are becoming difficult to dispose of. Findings reveal the nutrient deficiencies in the soil surrounding the mining waste disposal site making it unfit for plant growth, which is detrimental to the agricultural industry (Paramasivam and Anbazhagan 2020). These wastes usually require a large amount of space for storage, which can negatively affect the environment and ecology and be costly (Benarchid *et al*. 2019). Recent studies show tailings from magnesite mines were treated with cement and used as a subgrade for road construction

(Shanmugasundaram and Shanmugam 2023). Incorporating MGW in concrete has several ecological benefits, such as protecting the natural resources of Mother Earth, increasing the amount of waste materials that are converted from landfills into useful products, decreasing the emission of CO_2 and other greenhouse gases into the environment, promoting sustainable construction and saving a significant amount of energy and money.

1.5. Self-compacting concrete (SCC)

SCC is one of the revolutionary concretes that is increasingly being utilized for research as well as real-time projects. It can flow effortlessly under its own weight and consolidate on its own without mechanical vibration. Concrete needs to possess exceptional deformability and stability in order to guarantee an excellent formwork-filling capability, especially in densely packed structural components. Kannur and Chore (2023) stated that opting for SCC increases the project's cost because it needs a lot of fines or cementitious materials ranging from 450 to 650 kg/m^{3,} which involves high energy consumption as well as CO_2 emission (Kannur and Chore 2023b). Even though SCC has its own advantages over ordinary vibrated concrete, other demerits such as high fines or cement content, energy consumption and CO_2 emission are to be addressed. This paved the way for introducing a hybrid form of SCC known as low-fines self-compacting concrete.

1.6. Low-fines Self-compacting concrete

Low-fines SCC exhibits the same properties as conventional SCC but with low-fines or cementitious content ranging from 350 to 550 kg/m^3 of concrete, which approximately reduces 100 kg of binder per cubic meter of concrete production (Kannur and Chore 2023b). Technically, in 2009, BASF construction chemicals announced a commercial name for the low-fines self-compacting concrete as Self Dynamic Concrete (SDC) (with SF1 flow type, i.e., 550 to 650mm flow diameter), which combined the advantages of conventional vibrated concrete (stability) and conventional SCC with high fines (flowability characteristics) (Ammasi *et al*. 2017). Generally, SCC speeds up construction as it is less time-consuming and allows construction to be done without making any noise (without using a needle vibrator for external compaction). Additionally, the low-fines SCC also permits using by-products from industrial sectors in manufacturing, resolving the issues of depleting natural resources, use of virgin or conventional materials, and waste disposal that could otherwise result in pollution of land and water (Kannur and Chore 2023c). Few studies reported that this special type of SCC is also suitable for waste replacement in place of conventional materials, which is economical, environmentally friendly, and energy efficient as it saves time and money, and reduces CO_2 emission (Christensen and Huebsch 2012; Balakrishnan *et al*. 2016; Vembu and Ammasi 2024).

1.7. Research significance

Numerous studies were conducted to examine the rheological properties of SCC using mineral admixtures and industrial waste products in place of cement. However, the study on low-fines SCC incorporated with mining waste is yet to be explored, especially with the wastes generated from magnesite mines. Hence, this study explores the applicability of wastes from magnesite mines as a potential replacement for cement in low-fines SCC with binary (cement + 1 SCM, i.e. mine waste) and ternary (cement + 2 SCMs, i.e. fly ash and mine waste) blended combinations.

2. Experimental methodology

2.1. Materials

Ordinary Portland cement (Grade 53), having specific gravity and surface area of 3.14 and 420 kg per square meter, respectively, with setting times of 75 min (initial) and 420 min (final), was used. Locally available M-sand with a specific gravity of 2.56, bulk density of 1697 kg per cubic meter, water absorption of 2.56% and fineness modulus of 2.83 (medium sand category) was used as fine aggregate. Locally available crushed granite stones (maximum size 12.5 mm) with a specific gravity of 2.71, bulk density of 1400 kg per cubic meter, and water absorption of 0.75% were used as coarse aggregates. For concrete mixing and curing, potable tap water was utilized. Polycarboxylic ether-based superplasticizer with a specific gravity of 1.08 was used as a chemical admixture as per the requirements for retaining the workability of the SCC mixtures. Waste from magnesite mines and fly ash from thermal power station was replaced for cement. Mine waste and fly ash had specific gravities of 2.7 and 2.1, respectively. Major chemical compositions of different materials employed in the investigation are shown in Table 2.

Table 2. Oxide concentrations of different materials in percentage (%)

Component	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Others
Cement	17.9	0.25	3.78	5.39	63.2	2.76	1.43
Fly ash	57.9	1.71	31.4	4.52	1.21	0.72	2.14
M-sand	61.1	0.56	15.4	4.95	5.04	3.03	9.34
Mine waste	34.1	0.06	2.24	8.87	6.06	47.4	0.57

2.2. Mix design and procedure

To meet the flow criteria, the SCC mixtures were designed based on IS 10262 (2019) and EFNARC (2005) recommendations (EFNARC 2005; IS 10262 2019). The aim was to develop an eco-friendly and economical low-fines self-compacting concrete, and hence, the total cementitious content was fixed at 389 kg/m^3. Waste from magnesite mines was replaced for cement in binary and ternary blended SCC mixtures at 10%, 20% and 30% by weight of cement, and Class F fly ash was replaced for

20% of cement by weight in ternary blended SCC mixtures. The W/B ratio was maintained at 0.45 and superplasticizer dosage was varied from 0.5% to 0.9% to the weight of cement as per the workability requirements of the mixtures. Mixing of concrete was performed in the laboratory using a pan mixer of 0.1 m^3 capacity as per the recommendations of ASTM C192/C192M (ASTM C192/C192M 2016). Mix proportioning of materials adopted in the study are given in Table 3.

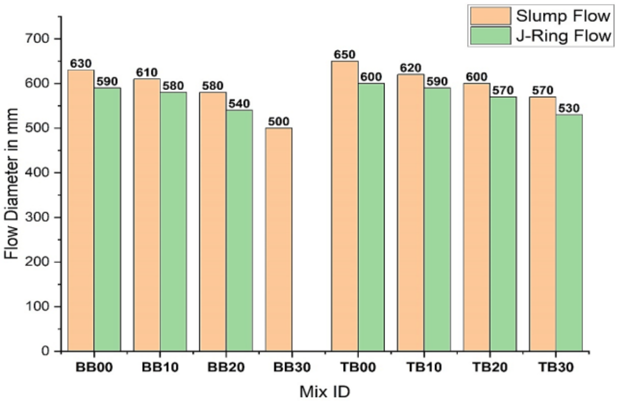
Table 3. Mix proportioning of SCC in kg per cubic meter

Mix ID	Cement	Fly ash	Mine Waste	M-sand	Aggregates	Water	SP
BB00	389	0	0	960	840	175.05	2.33
BB10	350.10	0	38.90	960	840	175.05	2.33
BB20	311.20	0	77.80	960	840	175.05	3.11
BB30	277.30	0	116.70	960	840	175.05	3.50
TB00	311.20	77.80	0	960	840	175.05	2.33
TB10	272.30	77.80	38.90	960	840	175.05	1.95
TB20	233.40	77.80	77.80	960	840	175.05	2.72
TB30	194.50	77.80	116.70	960	840	175.05	3.11

BBXX – SCC with binary cement blend (cement + mine waste), TBXX – SCC with ternary cement blend (cement + fly ash + mine waste), XX – Percentage replacement of mine waste (0%, 10%, 20%, 30%)

2.3. Casting and testing

Tests in the fresh state, such as filling ability (slump-flow, V-funnel, T_{50cm}) and passing ability (L-box, J-ring), were performed as soon as the fresh mixture was made to assess the fresh characteristics of the low-fines SCC mixtures in accordance with standard requirements (EFNARC 2005; IS 10262 2019). Immediately after assessing the fresh properties, the casting of concrete into the moulds was completed to determine the hardened properties such as compressive strength (7, 28, and 90 days), flexural strength and splitting tensile strength (28 and 90 days). The cast specimens were demolded after 24 hours and placed in the curing tank. The specimens of sizes 150x150x150mm, 100mm diameter x 200mm depth, and 500x100x100mm were used for evaluating compression, splitting tensile, and flexural strengths, respectively (BIS:5816 1999; IS:516 Part-1/Sec-1 2021). The strength parameters obtained by the mixtures were supported by SEM analysis. To determine the monetary significance of utilizing MGW in SCC as a binder, the costs of each mixture were analyzed. To learn more about the environmental benefits of using MGW in SCC, CO_2 emission and embodied energy analysis were done using embodied coefficients of materials used in the production of SCC.



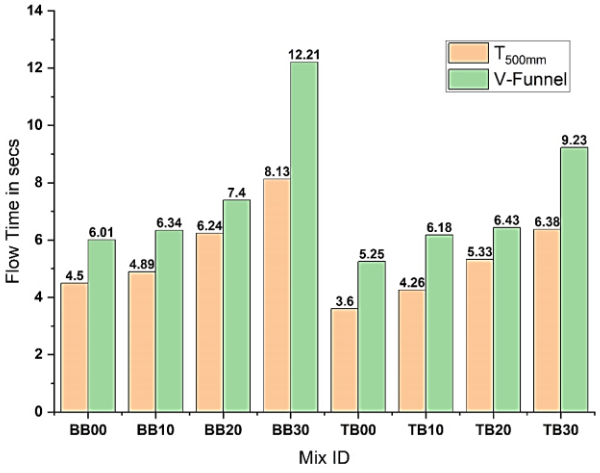


Figure 1. Fresh property results of blended SCC mixtures

3. Results and discussions

The laboratory experiments were carried out, and their results are discussed below,

3.1. Fresh properties

The four important characteristics, such as flowability, passing ability, viscosity, and segregation resistance describe self-compacting concrete's stability and its capacity to fill and compact under its own weight (Güneyisi 2010). Figure 1 shows the test results of flowability and filling abilities, whereas Table 4 provides the results of passing ability.

3.2. Blended SCC mixtures

The results from Figure 1 indicate that the slump flow of mine waste incorporated binary blended SCC (BB10, BB20, BB30) exhibited a slight to heavy drop in slump flow. In contrast, ternary blended SCC (TB10, TB20, TB30) exhibited notable reduction compared to the control mixtures BB00 and TB00, respectively. Especially the BB30 mix that did not meet the workability necessities of EFNARC and IS 10262 which requires a minimum slump flow of 550mm for SCC mixtures. Observations reveal that the mix combinations fall under the SF1 flow category, which has slump flow diameters between 550 and 650mm, with 650mm being the highest and 570mm being the lowest, except for the BB30 mix, which achieved only 500mm slump flow. Almost all the mixtures showed flow in the range of 600 to 630mm, demonstrating the homogeneity of the mix design and allowing it to be used in members of reinforced concrete. T_{50cm} test results revealed the uniformity in the flow of the SCC mixtures, as they covered 50cm flow in 4 to 6 seconds (Güneyisi 2010). From the V-funnel test results, it can be observed that VF_1/V_1 category of viscous flow was exhibited by both binary and ternary blended SCC mixtures till 20% replacement, above which SCC mixtures fall under VF_2/V_2 viscous flow category.

Table 4. Passing abilities of SCC mixtures

Mix ID	**BB00**	**BB10**	**BB20**	**BB30**	**TB00**	**TB10**	**TB20**	**TB30**
L-box test (h_2/h_1 ratio)	0.83	0.82	0.8	NR	0.88	0.95	0.85	0.81
J-ring h_2-h_1 (mm)	0	1	3	NR	1	1	1	2

NR – Did not pass the test or failed to attain the minimum value.

In the L-box testing, the h_2/h_1 ratio of all mixtures was recorded in the range of 0.81 and 0.95 with three bar testing (recommended for severely congested reinforcement), progressing in accordance with the requirements of the EFNARC and Indian Standards. This indicates that the L-box test results of SCC combined with mine waste functioned effectively in passing ability. In the J-ring test, all concrete mixtures performed well because the concrete never failed to pass past the obstruction created by the 10 mm diameter reinforcement bars attached to the ring. Comparing the results, it can be seen that all SCC mixtures experienced an average drop in flow diameter of about 40mm, falling within the minor blockage zone of ASTM C1621 (2009), with the exception of the mix containing 30% mine waste in binary blended SCC, which failed to flow above 500mm in slump flow test (ASTM C1621 2009). When the height difference (blockage step) across the J-ring setup is analyzed, it is found that almost all the SCC combinations performed in accordance with the requirements of the EFNARC recommendations; specifically, h_2-h_1 of all the mixtures were lesser than or equal to 3mm, which is significantly less than the maximum value of 10mm. This demonstrates conclusively that all SCC mixtures have significant passing abilities. Observations from Table 2 reveal that superplasticizer dosage increased with the rise in mine waste replacement from 2.33 to 3.5 kg/m^3. Despite an increase in admixture dosage, the minimum slump flow of 550mm was not achieved in the BB30 mix. At the same time, 30% of mine waste combined with 20% fly ash (ternary blend) achieved a flow diameter of 570mm, which shows the ability of fly ash to improve the workability of SCC (Güneyisi 2010). The presence of MgO in MGW might result in the formation of $Mg(OH)_2$ (expansive product) upon addition of water, which could be the reason for the reduced workability in concrete mixtures (Ruan and Unluer 2017).

3.3. Binary vs ternary blended SCC mixtures

According to the outcomes of the slump flow tests, almost all SCC mixtures can be grouped under the flow category of SF_1. As the mine waste replacement increased, the flowability of SCC gradually decreased. A similar trend can also be applied to T_{50cm} flow with VS_2 category, where the time to flow through a 500 mm diameter increased as the replacement levels of mine waste increased. MGW as cement replacement decreased the fluidity of the mixtures for the same powder type and amount. However, due to their practically large bounds, the rheological classes of SF_1, VF_1/V_1, and PA_2 were unaffected. Comparing the BB and TB series, the TB mixtures performed better than the BB mixtures especially for the higher replacement levels of mine waste (30%). For the respective replacement levels, the ternary blended SCC mixtures perform up to 14% better than binary blended SCC mixtures. The presence of fly ash was the primary cause as it improved the workability of concrete, which also acts as an alternate to viscosity modifying agent (Pop *et al*. 2015).

3.4. Hardened properties

Strength tests were performed on all SCC mixtures for compression, splitting tensile, and flexural properties. Splitting tensile strength emphasizes the material's resistance to localized tensile stresses, whereas compressive and flexural strength represent the material's total load-bearing capacity upon compression and bending, respectively. The test results of the hardened properties of various SCC blends are described in Figure 2.

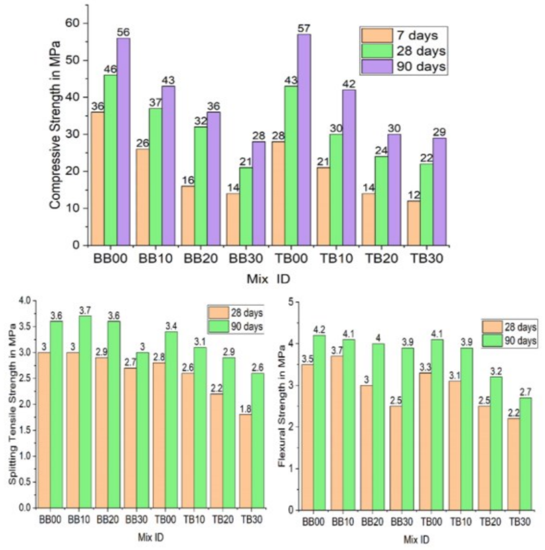


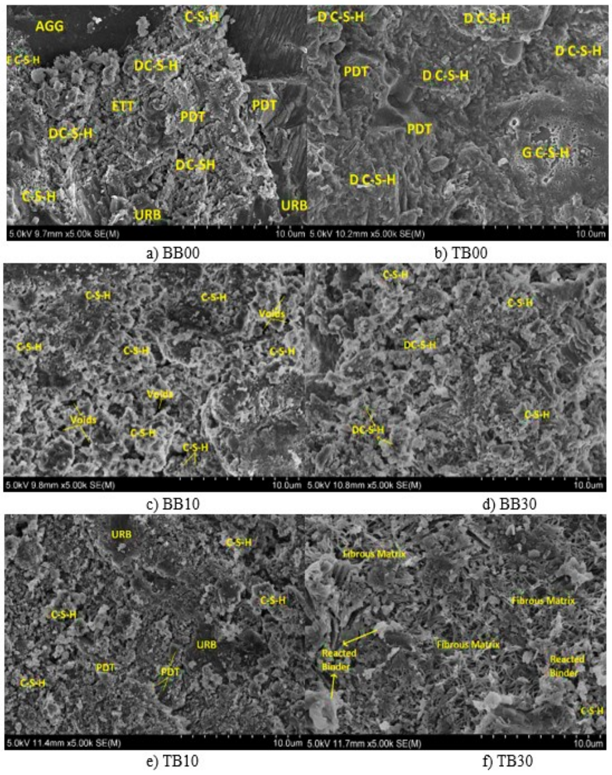
Figure 2. Hardened strength results

3.5. Blended SCC mixtures

Figure 2 displays the findings from the flexural, splitting tensile, and compressive strength tests conducted on each SCC mixture. The findings show that the strengths of

SCC mixtures generally declined as mine waste replacement dosage increased. However, the type (binary or ternary) and quantity of mine waste binder used determines the rate at which strength is decreased. Binary blended SCC mixtures exhibited compressive strength in the range of 21 to 37.2 MPa and 28.1 to 42.9 MPa at 28 and 90 days, respectively. Similarly, TB mixtures displayed strength in the range of 21.7 to 30.1 MPa and 28.6 to 41.5 MPa at 28 and 90 days, respectively. The obtained compressive strengths were compared with their respective control mixtures namely BB00 and TB00. Compressive strength is one of concrete's most important mechanical attributes, which can occasionally be utilized to evaluate how well the hardened concrete will function overall throughout the structure's service life (Güneyisi *et al*. 2014). Compressive strengths of SCC with blended mine waste gradually decreased after raising the mine waste replacements regardless of the type of blending (BB or TB). BB and TB mixtures exhibited a strength loss of up to 60% at 7 days, which gradually decreased to 50% at 90 days. This shows that the mine waste as a binder gains compressive strength at a higher proportion than the conventional cement-based SCC mixtures upon ageing. The additional water requirement was adjusted by increasing the superplasticizer dosage to improve/maintain the workability, as shown in Table 2 might also be a reason for strength reduction in SCC mixtures in addition to the reduced cement content.

Data from Figure 2 shows that the splitting tensile strength is slightly reduced upon replacing cement with mine waste. In particular, ternary blended (TB) mixtures exhibited a higher loss in strength compared to binary blended (BB) mixtures similar to compressive strength results. BB mixtures exhibited equal (BB 10) or up to 10% loss (BB20 and BB30) at 28 days, while at 90 days of testing, it showed improvement (BB10 3%), equal (BB 20) and decreased (BB30 20%) strength. Strength improvement is because the matrix's pores are constantly being filled with strength-enhancing hydration products like C-S-H gels, which look denser in the matrix (D C-S-H) shown in Figure 3. On the other hand, TB mixtures reduced the strength up to 36% at 28 days and up to 24% at 90 days respectively. This can be addressed as the higher reduction in conventional cement binder automatically reduces strength when replaced with alternate materials which exhibit lesser oxides of calcium and silica (as per XRF results in Table 2). Comparing the flexural strength results from Figure 2; it can be observed that BB mixtures exhibited a slight improvement (BB10 – 6%) and reduced strengths (BB20 – 14% and BB30 – 29%) at 28 days and slight reduction of up to 7% at 90 days respectively. On the other hand, TB mixtures reduced the strength by up to 34% at both 28 and 90 days. Similar to compressive strength, the flexural strength developed at a faster rate in ternary blended mixtures than in binary blended mixtures which adds to the slow pozzolanic property in the combination of MGW with fly ash. This might be due to the presence of MgO that activates the SCM present in the concrete mixture, resulting in the development of M-S-H and additional C-S-H (Yi *et al*. 2014).



a) BB00 b) TB00

c) BB10 d) BB30

e) TB10 f) TB30

Figure 3. SEM images of samples evaluated

3.6. Binary vs ternary blended SCC

An interesting thing to note is the ability of mine waste to gain strength upon ageing, especially in combination with fly ash (TB series), as the rate of gain is higher in mine waste incorporated SCC mixtures than cement-based SCC mixtures (BB series). It can be seen that BB (BB10, BB20, BB30) mixtures gained a maximum compressive strength of 128% from 7 days to 90 days, whereas TB (TB10, TB20, TB30) mixtures gained a maximum of 150% during the same time duration. On the contrary, conventional SCC mixtures like BB00 and TB00 gained a maximum compressive strength of 56% and 106%, respectively, for the same time duration. Splitting tensile and flexural strength results also go in hand with the compressive strength results in terms of strength gaining as TB mixtures gained higher strength than BB mixtures upon ageing, irrespective of the percentage of replacement of cement with MGW. Even though the strength obtained by BB and TB mixtures differ with the same amount of mine waste replacement, it is noteworthy that the TB30 (50% cement and 50% SCM) mix obtained similar or slightly higher strength than BB30 (70% cement and 30% SCM) which greatly contributes to the eco-efficiency of the SCC mixtures. This clearly revealed the fact that MGW exhibits some pozzolanic properties similar to fly ash, and when mine waste is combined with fly ash in addition to cement, another 20% gain can be achieved, which also adds credit to the sustainability concepts. Also, the additional silica from MGW combined with fly ash would have slightly increased the strength of TB30 over its counterpart mixture of BB30.

3.7. SEM analysis

Understanding the microstructure of concrete is crucial for assessing its strength characteristics. Scanning electron microscopy (SEM) was used to evaluate the development of cement hydration products, including C-S-H, portlandite (PDT), and ettringite (ETT), in order to study the microstructure of concrete. By examining the microstructure of the concrete, SEM analysis relates the strength parameters gained by the integration of various elements (Sandhu and Siddique 2019). The interfacial transition zone (ITZ), hydrated cement paste, and aggregates form the majority of the microstructure of concrete (Meena *et al*. 2023). The water-binder ratio, admixtures, cement type, and duration of the hydration process all have a significant impression on the microstructure of concrete. Because they speed up cement hydration reactions and optimize pore distribution, fly ash and superplasticizers play crucial roles in microstructure by resulting in a denser matrix (Zhu *et al*. 2023). At the age of 28 days, SEM analysis was carried out on all mixtures using samples obtained from cube specimens used to investigate compressive strength. The images of the samples that performed better in terms of compressive strength are presented in Figure 3.

At the age of 28 days, the development of C-S-H gel, PDT, and ETT has been detected based on the study of the SEM images. There was evidence of primary ettringite formation (thin needle-like structure) in BB00, which was surrounded by DC-S-H (denser variant) gel that creates a bridge between different C-S-H layers resulting in stronger and more compact matrix in the concrete (Mu *et al*. 2023). The C-S-H gel and PDT formation were frequently observed in BB00, BB10, TB00 and TB10 mixtures responsible for strength gain. C-S-H gel formation was more predominant in BB mixtures than TB mixtures, which may be due to the absence of higher amounts of cement (CaO-rich material) in the latter. Additionally, the presence of voids in the BB30 mixture supports the lesser strength achieved by the mixture. In the case of TB30, there was no clustered C-S-H gel formation observed, instead only fibrous matrices were seen, which validates the inefficiency of the mix to develop strength at 28 days. Another noteworthy finding is that fly ash, which speeds up the pozzolanic process and minimizes voids in the concrete matrix, makes the C-S-H formation more likely to occur in combinations of TB mixtures, which is lacking in BB mixtures. Hence, the voids were observed in the microstructure of BB30 as a result of which strength was reduced drastically. While for the same 30% replacement in TB mix, the strength achieved was slightly higher than BB30 mix despite the absence of an additional 20% of total cement. Additionally, a stronger bond between the surrounding cement paste and the aggregates was seen, enabling an even distribution of loads without any segregation. There were no evident cracks in the microstructure of SCC mixtures, which shows better bonding in the concrete matrix.

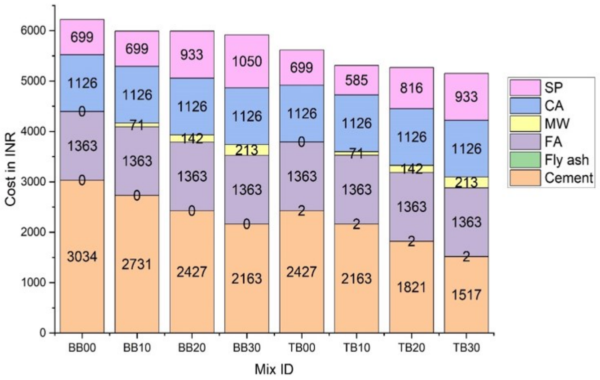


Figure 4. Cost involved in producing 1m3 of SCC

Table 5. Material cost

Description	Unit	C_m (INR)	Transportation Cost (C_{tc})			Total Cost C_{tmc} (C_m+ C_{tc})	
			Distance in km	Rate/ unit/km	Total (INR)	INR	USD
Cement	tonne	7200	10	60.00	600	7800	95.12
Fly ash	tonne	0	3	10.00	30	30	0.37
FA	tonne	910	3	170.00	510	1420	17.32
CA	tonne	830	3	170.00	510	1340	16.34
MW	tonne	0	330	5.52	1822	1822	22.22
Water	kg	-	-	-	-	-	-
SP	kg	300	-	-	-	300	3.66

Table 6. Embodied energy and CO_2 emission factor of materials

	Cement	Fine Aggregate	Coarse Aggregate	Water	Admixture
CO_2 emission per kg	1.25	0.006	0.006	0.0003	0.72
Embodied energy per kg	4.8	0.081	0.083	0.2	11.5

For international conversion, the average rate of 1 USD = 83 INR can be fixed as per April trends in 2024

3.8. Cost, CO_2 emission and energy analysis

The investigation of concrete's costs, energy and CO_2 emissions is crucial since these factors are necessary for ensuring the production of environmentally friendly and economically beneficial concrete. To evaluate the ecological impacts of concrete production, it is essential to understand its carbon footprint. In contrast, analyzing the manufacturing cost aids in finding the areas where costs can be reduced for economically advantageous applications. The cost, CO_2 emission and energy consumption involved in producing concrete can be determined using the following equations: 1, 2 and 3, respectively. Data for evaluating cost, energy and CO_2 emission are taken from Tables 3, 5 and 6. Table 5 represents the price of the materials used including transportation cost. Distance between the vendor location and the laboratory was taken into consideration and the rate/unit/km was calculated by dividing the price charged by the goods transport vehicle company. Figure 4 represents the cost analysis report, while Tables 7 and 8 present the CO_2 emission analysis and energy consumption of various SCC mixtures. Figure 5 shows the savings achieved in cost, CO_2 emission and embodied energy upon incorporating mine waste as partial binder replacements in SCC. The cost of materials was taken from the Schedule of Rates 2023-2024 prescribed by the Government of Tamil Nadu, India while the CO_2 emission factor and energy factor was obtained from the previous work (Hu *et al*. 2022; Schedule of Rates 2022).

$$Cost\ involved = Q_m \times C_{tmc} \quad (1)$$

$$Material\ cost\ = C_m + C_{tc} \quad (2)$$

$$CO_2 emission\ involved\ = Q_m \times F_c \quad (3)$$

$$Energy\ consumed\ = Q_m \times E_e \quad (4)$$

Where,

Q_m - Material quantity, kg/m^3

C_{tmc} - Total material cost, INR

C_c - Unit material cost, INR

C_{tc} - Material transport cost, INR

F_c - Materials' CO_2 emission factor, $kgCO_2$ per kg

Ee- Embodied energy of materials, MJ/kg

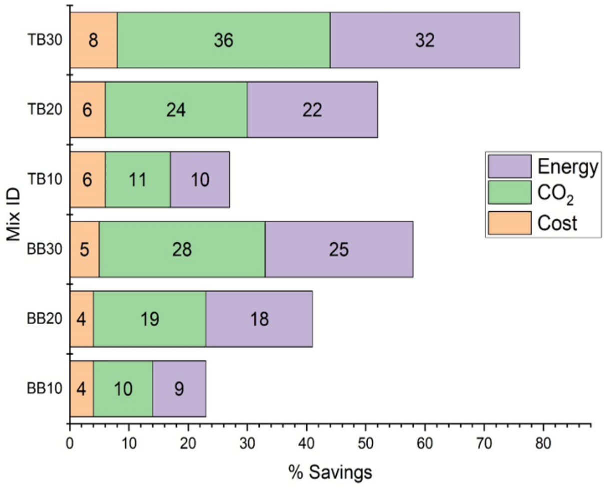


Figure 5. Savings in cost and CO_2 emission against BB00 and TB00

Table 7. CO_2 emission per cubic meter of SCC

Mix ID	BB00	BB10	BB20	BB30	TB00	TB10	TB20	TB30
Cement	486.25	437.63	389.00	346.63	389.00	346.63	291.75	243.13
M-sand	5.76	5.76	5.76	5.76	5.76	5.76	5.76	5.76
Stones	5.04	5.04	5.04	5.04	5.04	5.04	5.04	5.04
Water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
SP	1.68	1.68	2.24	2.52	1.68	1.40	1.96	2.24
Total	498.78	450.16	402.09	360.00	401.53	358.88	304.56	256.22

Table 8. Embodied energy per cubic meter of SCC in MJ

Mix ID	BB00	BB10	BB20	BB30	TB00	TB10	TB20	TB30
Cement	1867	1680	1494	1331	1494	1331	1120	934
M-sand	78	78	78	78	78	78	78	78
Stones	70	70	70	70	70	70	70	70
Water	35	35	35	35	35	35	35	35
SP	27	27	36	40	27	22	31	36
Total	2076	1890	1712	1554	1703	1536	1334	1152

Figure 4 shows that the cost of making 1 m^3 of concrete decreased as the replacement of mine waste increased for both binary (BB series) and ternary (TB series) blended SCC mixtures. From Figure 5, it is evident that the combination of cement and mine waste (BB series) reduces up to 5% of production cost, while the combination of cement, mine waste and fly ash (TB series) reduces up to 8% which is quite a massive sum upon running mass concrete works. Cement is quite expensive than aggregates and less expensive than admixture; however, admixture is used at a lower rate than cement. The role of the superplasticizer was vital since it was necessary to improve/retain the flowability and workability of SCC consisting of MGW without sacrificing their strength and durability. As a result, the price of the superplasticizer increased when mine waste was used to make SCC, but this increase in cost was taken care of by the cost of mine waste replacements. A similar trend was observed in CO_2 emission and energy analysis as replacing cement with mine waste proves to be more advantageous in conditions of reducing CO_2 emission and energy consumed because a major contributor to the world's greenhouse gas (GHG) emissions is the cement industry. It can be observed that the CO_2 emission started from 498.78 $kgCO_2/m^3$ (BB00) and ended up in 360 $kgCO_2/m^3$ (BB30) for binary blended SCC which saved around 28% of total CO_2 emission, whereas for ternary blended SCC it was 401.53 (TB00) $kgCO_2/m^3$ and 256.52 (TB30) $kgCO_2/m^3$ which save around 36%. By partially substituting mine waste for cement, it is possible to obtain a significant decrease in CO_2 emissions in the range of 6% to 9% for the BB series and 11% to 36% for the TB series. At the same time, embodied energy involved in the production of SCC can also be impacted by replacing cement with mine waste. Embodied energy involved in binary blended SCC mixtures decreases from 2076 to 1554 MJ/m^3 upon mine waste replacement, while for ternary blended SCC mixtures, the energy decreases from 1703 to 1152 MJ/m^3. It can be noticed that the BB series saves up to 25%, and the TB series saves up to 32% of the total energy consumed to produce 1 m^3 of SCC. The Sustainable Development Goals (SDG), set by the United Nations aimed at 2030, are greatly aided by this cost, energy and CO_2 emission reduction. To be more precise, introducing mine waste into concrete contributes to reaching SDGs 9 (Indicators 9.4.1) and 12 (Indicators 12.2.1 - Material footprint, Target 12.5), as well as promoting sustainability in the industrialization, production, and consumption in the construction sectors. Specifically, Target 9.4, which measures CO_2 emissions per unit of value added, and Target 12.5, which aims to significantly reduce waste output through prevention, lessening, recycling, and reuse, are supported by the replacement of MGW in SCC (Krehbiel *et al*. 2017).

4. Conclusions

This study examined the feasibility of replacing cement with magnesite mine wastes in self-compacting concrete, which is one of the unexplored sustainable building materials. A number of laboratory experiments were carried out, and the results mostly showed that MGW can be used to make self-compacting concrete. The properties of SCC benefited from the use of MGW as a substitute for cement because it fulfilled the required fresh properties as per the standards of IS 10262 (2019) and EFNARC (2005). The filling and passing ability results demonstrated that SCC blended with MGW for a portion of the cement in combination with fly ash (ternary blend) performed better than SCC mixtures that used binary blend in terms of fresh properties. Comparing the compressive strength results, both binary (BB10, BB20, BB30) and ternary blended (TB10, TB20, TB30) SCC mixtures exhibited lesser strength than their respective control concrete mixtures (BB00 and TB00) irrespective of the age of testing. Both binary and ternary blended mixtures exhibited up to 60% loss in compressive strength at an early age, while the difference was reduced to 50% upon ageing. Notably, the binary blended SCC mixtures exhibited higher strength loss compared to the ternary blended mixtures, which shows the influence of fly ash. Splitting tensile and flexural strength results slightly varied from the compressive strength results as the lesser dosage of mine waste in binary blended SCC exhibited lesser improvement in strength of up to 6%. In comparison, all the ternary blended mixtures showed a loss in strength up to 35%, irrespective of the curing days. SEM images validate the strength properties achieved by both binary and ternary blended SCC mixtures as C-S-H gel formations were seen in lesser dosages on mine waste incorporated concrete (both BB and TB), while the voids and fibrous matrix were observed for higher dosages of mine waste. Cost, CO_2 emissions, and energy analysis offered a clear idea of how MGW impacts the economic and ecological aspects of the construction industry as it saves up to 8% of cost, 36% of CO_2 emission and 32% of energy consumed when partially replaced for cement. In addition, introducing MGW as an alternate construction material in the concrete industry highly promotes the SDGs adopted by the UN by contributing to SDGs 9 (Industry, Infrastructure and Innovation) and 12 (Responsible Consumption and Production). When all the findings are summed up, it becomes clear that the waste from magnesite mines has a bright future as a substitute for traditional building materials, especially cement. By effectively reusing MGW, which is currently disposed of as landfills the proposed method supports sustainable construction by producing concrete with less natural resources and energy. By reducing the effects of global warming, using mining waste will safeguard the environment and generate low-cost, environmentally friendly concrete.

Future recommendations

The mechanical and fresh properties of SCC blended with waste from magnesite mines as a partial cement replacement have drawn a significant amount of interest in this study. To ensure that the suggested concrete blend is reliable, it is suggested to inspect its feasibility in aggressive conditions. It is possible to assess the viability of utilizing the waste from magnesite mines as a substitute for conventional vibrated concrete, geopolymer concrete, and other forms of concrete.

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