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RESEARCH

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Using Municipal Solid-Waste Incinerator Fly Ash, Wash Water, and Propylene Fibers in Self-Compacting Repair Mortar, Greenhouse Gas Emissions Potential

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Abstract

Wash water, municipal solid waste incineration (MSWI) fly ash, and propylene (PP) fibers were employed simultaneously to produce self-compacting repair mortar (SCRM). Different SCRM mixtures were utilized, incorporating 35, 70, and 140 kg/m^3 of MSWI fly ash, along with 0.1% of PP fibers. The research focused on investigating the workability, mechanical properties, and global warming potential (GWP) of SCRM. The incorporation of MSWI fly ash and wash water in SCRM resulted in reduced workability, necessitating an increase in the use of superplasticizer. Adding MSWI fly ash decreases compressive strength. The minimum compressive strength was observed when employing 140 kg/m^3 of MSWI fly ash and wash water instead of tap water simultaneously. By increasing the proportion of MSWI fly ash content and correspondingly reducing the cement content in SCRM samples, there was a decrease in flexural strength. The ultrasonic pulse velocity (UPV) of all SCRM samples falls within acceptable range. Adding MSWI fly ash to SCRM reduces fracture toughness, and the concurrent use of wash water and MSWI fly ash significantly decreases fracture toughness. Incorporating PP fibers into SCRM resulted in increased compressive strength. Utilizing wash water and MSWI fly ash in SCRM significantly reduces GWP. The avoidance of wash water consumption mitigates the environmental impact of SCRM.

Keywords Self-compacting repair mortar, MSWI fly ash, Fracture toughness, GWP, Avoided product

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1 Introduction

Population growth has increased the demand for freshwater for drinking and industrial use (de Matos et al., 2020). Concrete is the second most-consumed material after water; increasing construction is always associated with increased freshwater consumption. Finding a suitable replacement for freshwater that could maintain the mechanical and durability properties of concrete and be environmentally sustainable is a major challenge for engineers. In a concrete plant, for each cubic meter of concrete production per year, about 0.077 tons of wash water and slurry are produced from the ready-mixed concrete plants and mixer trucks (Chen et al., 2022). The economic benefits for concrete plants could be offset by the environmental benefits of reusing wash water.

SCRM are specially used to rehabilitate and repair reinforced concrete structures. This SCRM is also mainly used in places where vibration is impossible (Felekoglu et al., 2007). Several studies have been conducted utilizing wash water in both conventional and SCC. In Borger et al.'s study (1994), wash water was employed to produce concrete. They asserted that wash water has the potential to enhance the compressive strength by up to 20% in comparison to freshwater. Sandrolini and Franzoni (2001) found that using wash water in concrete maintained 96% of the 28-day compressive strength compared to fresh water, albeit with slightly reduced workability due to fine particles. Chini et al. (2001) and Su et al. (2002) demonstrated wash water's compliance with ASTM C94 standards (2003) for compressive strength and setting time. Chatveera et al. (2006) observed that incorporating sludge from concrete plants reduced strength properties but remained within ASTM C94 (2003) limits for compressive strength, with decreasing workability as sludge content increased.

Chatveera and Lertwattanaruk (2009) found that while sludge reduced sample compressive strength, adding superplasticizers and fly ash increased it, enhancing concrete durability. Tsimas and Zervaki (2011) showed wash water from different concrete plant parts as a viable alternative to fresh water. Wasserman (2012) observed higher 28-day compressive strength in specimens made with wash water. Asadollahfardi et al. (2015) noted the highest compressive strength in samples with a 50% wash water and 50% tap water mixture.

Vaičiukynienė et al. (2020) discovered that using sludge reduced cement sample strength, while adding 10% zeolite increased 28-day compressive strength by 20%. Yet, higher zeolite percentages decreased compressive strength. de Matos et al. (2020) studied the impact of various wash water concentrations on concrete hydration and properties. They found that due to high solid particles and alkalinity, yield stress and viscosity increased while slump decreased in the mortar. Cement hydration and compressive strength investigations revealed an early increase in strength at 3 and 7 days.

Bahraman et al. (2021) found that in SCC, replacing wash water with freshwater reduces workability but keeps it within ICAR System recommendations. Wash water use in SCC reduces 28-day compressive strength by 5% but increases flexural strength by around 3%. Aboelkheir et al. (2021) found that using wash water did not affect the properties of hardened or fresh concrete. Compared to the control sample made with freshwater, both compressive and flexural strengths were over 90% higher. In Taghizadeh et al. (2021), obtained wash water decreased slump but increased compressive strength. However, after 90 days, compressive strength decreased. Flexural and tensile strength increased by 70% and 37%, respectively, compared to freshwater samples. Chen et al. (2022) studied that replacing 75% and 100% wash water improves by 20% the 28-day compressive strength of samples.

Today, incineration ash finds use in construction, geotechnical projects, renewable energy, and ceramics (Ferreira et al., 2003). Many cities grapple with municipal solid-waste disposal due to dwindling landfill space. Incineration presents a viable solution (Goh & Tay, 1993), with its roots traced back to American proposals in 1901 (Sun et al., 2016). While reducing initial waste volume significantly, incineration yields substantial solid residue (Ivan Diaz-Loya et al., 2012). However, due to toxic elements, MSWI fly ash is deemed hazardous waste (Chen et al., 2019). Waste incineration, a prevalent method for reducing municipal waste volume, faces scrutiny due to its toxic by-products (Ivan Diaz-Loya et al., 2012). Addressing the environmental impact of incinerator ash production remains a key focus for researchers (Garcia-Lodeiro et al., 2016).

MSWI fly ash includes 24–27% lime and some silicates and aluminosilicates, which can be used to produce cement powder. On the other hand, MSW Fly ash particles have a small aggregate size that could fill spaces in the concrete matrix (Ferreira et al., 2003). One of the applications of using MSWI fly ashes after sieving and separating metal particles is that, if they comply with toxicity characteristic leaching procedure (TCLP) limits, they can be used as cement additives (Huang et al., 2006). For this reason, in many studies (Garcia-Lodeiro et al., 2016; Knoeri et al., 2013), leakage tests have been analyzed on the samples in addition to evaluating the mechanical characteristics of concrete and cement made using fly ash. Lin et al. (2003) stated that MSWI fly ash slag could be used for up to 20% of the cement content in mortar without reducing the quality of the concrete. Aubert et al. (2004) used MSWI-treated fly ash in concrete, assessing its compressive strength, durability, and leaching behavior. Over 2 to 90 days, no impact on compressive strength was observed. Additionally, physical properties of fresh and hardened concrete remained unchanged, with leaching tests indicating minimal pollution suitable for road use. Hartmann et al. (2015) substituted Portland cement with MSWI fly ash at 25%, 30%, and 50%. They suggested pretreatment methods like washing to reduce heavy metals and organic pollutants, enabling MSWI fly ash usage. Up to 25% replacement of Portland cement showed no significant changes in compressive and flexural strengths. Garcia-Lodeiro et al. (2016) used MSWI fly ash and bottom ash in alkali-activated hybrid cement. Their blend, comprising 60% clinker and 40% ash, achieved acceptable 28-day strength. Leaching analysis indicated reduced hazardous metals from MSW fly ash and bottom ash with the hybrid cement.

Rehman et al. (2020) used MSWI ashes (fly ash and bottom ash) in concrete 3D printing. They found that increasing the ash replacement ratio reduced the 28-day compressive strength. Incinerator bottom ash was also noted to decrease initial and final strength. Liu et al. (2023) demonstrated that MSWI fly ash enhances OPC products. Steam curing accelerates hardening and increases strength, particularly in high MSWI fly ash mixes. It refines pore structure and reduces porosity. Both steam and carbonation curing improve early and long-term performance of MSWI fly ash-modified mortar in OPC products. Wi et al. (2024) used MSWI fly ash and natural gas in cement-based materials. Fly ash was washed with water and NaOH. Untreated and treated fly ashes replaced cement in mortar at varying percentages. Treatments significantly reduced alkaline and chloride salts. Mortars with treated fly ash showed similar or improved properties compared to those without MSWI fly ash, indicating the potential for using MSWI fly ash in cement-based materials. Li et al. (2024) investigated how CO_2 pressure, temperature, and w/c ratio impact CO_2 uptake and compressive strength when MSWI fly ash is added to mortar. It explores mechanochemical pretreatment to improve MSWI fly ash homogenization

Table 1 Chemical specifications and physical properties of the used cement

Compounds	Cement (%)	ASTM C150/C150M-17 (2015)	Property	Result	Specification
SiO_2	21.23	Min 20	Density (kg/cm^3)	3175	ASTM C150 (2015)
Al_2O_3	4.7	Max 6	Fineness, specific surface(m^2/kg)	394	ASTM C115 (2010)
Fe_2O_3	3.72	Max 6	Autoclave expansion, max (%)	0.16	ASTM C204 (2010)
CaO	62.43	–	Compressive strength (MPa)		ASTM C109 (2001)
MgO	3.26	Max 5	3 days	25.1	
SO_3	1.98	Max 3	7 days	30.7	
K_2O	0.72	–	28 days	44.9	
Na_2O	0.72	–	Time of setting (Minutes)		ASTM C266 (2020)
I. R	0.39	Max 0.75	Initial set	178	
Loss-On-Ignition (LOI)	1.72	Max 3	Final set	271	

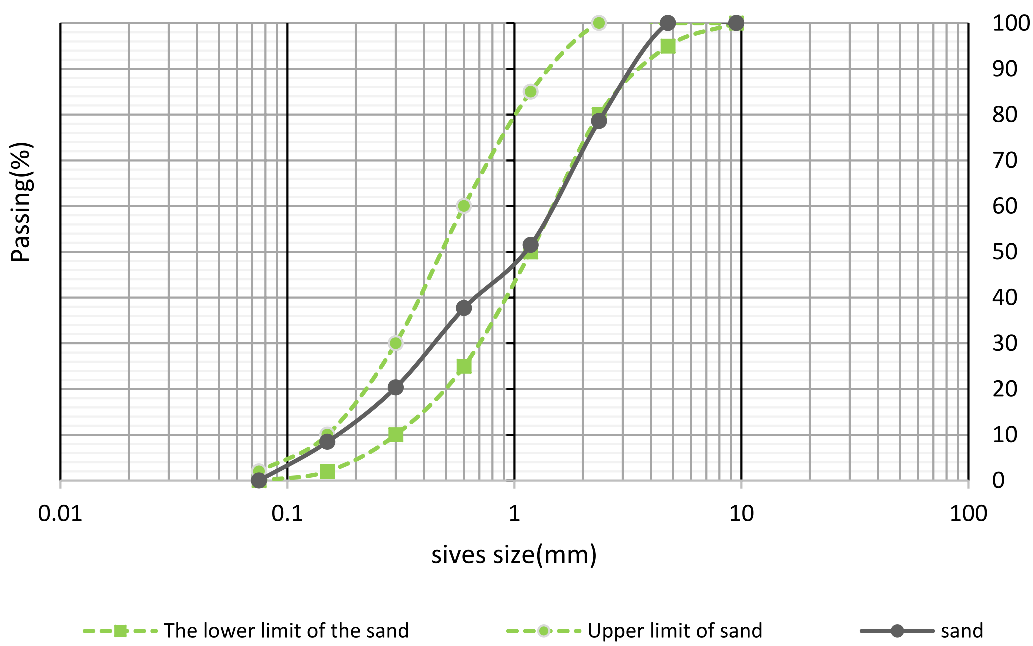

Fig. 1 Sieve analysis results in fine aggregate (sand(

Table 2 Specifications of MSWI fly ash

Oxide composition	wt%	Oxide composition	wt%	Oxide composition	wt%	Oxide composition	wt%	Oxide composition	wt%
Na	10.3	MgO	1.0	Al_2O_3	1.38	SiO_2	5.2	P_2O_5	1.1
SO_3	18.7	Cl	25.5	K	11.3	CaO	17.1	TiO_2	1.7
Fe_2O_3	2.7	CuO	0.07	ZnO	0.68	PbO	0.15	L.O.I	3.12

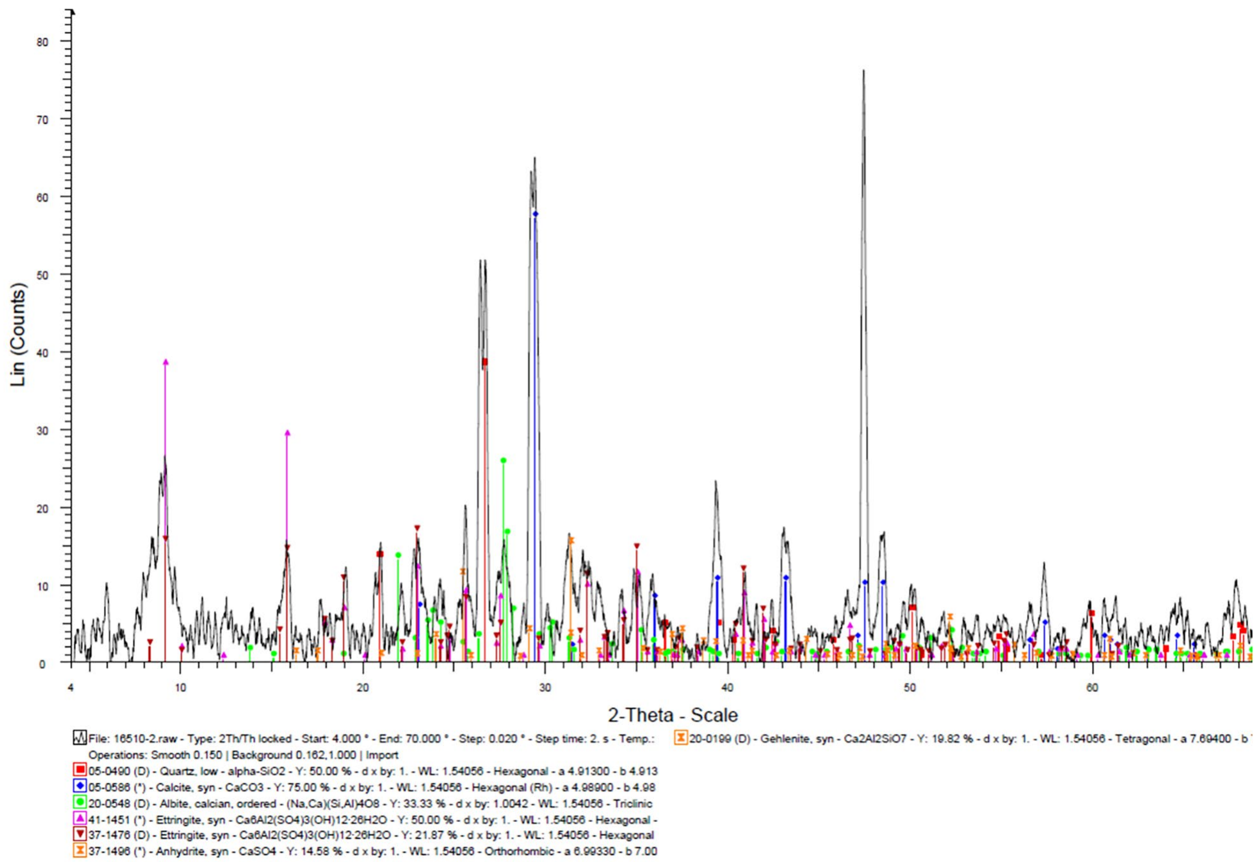

Fig. 2 XRD of the municipal solid-waste incineration (MSWI fly ash)

Table 3 Specifications of fiber (Provided by the manufacturer)

Properties	Results
The type of fiber	Polypropylene
Length(mm)	6
Diameter/(μm)	23–35
Tensile strength (MPa)	400
Salt resistance	High
Elongation (%)	80
Acids and bases resistance	High
Melting point (Celsius)	160
Aspect ratio(L/D)	171–261
Maximum tensile strain (%)	80

and mortar microstructure density. Results show a 43.6% increase in 28-day compressive strength and reduced leaching of heavy metals.

As shown in studies, using wash water reduces the compressive strength of concrete, but in contrast, using MSWI fly ash increases the durability of the concrete; the higher ages of curing would have a higher compressive strength. The simultaneous use of these two materials represents a step towards sustainable development and will reduce the consumption of fresh water and cement in concrete.

Given the significance of LCA as a sustainability tool, we conducted a global warming analysis for various types

Table 4 Chemical properties of Tap water and wash water

Compounds	Unit	Tap water	Wash Water	ASTM C94-09(2003) specification
pH	NTU	7.79	13	
Turbidity	mg/L	1.2	33	
Sulfate (SO_4^{-2})	mg/L	24.5	439	≤ 3000
Chloride (Cl^{-1})	mg/L	14	191	≤ 1000
Total solid (TS)	mg/L	566	2575	≤ 50,000
Total dissolved solids (TDS)	mg/L	560	2380	
Total hardness	mg/L	201	1290	
Chemical Oxygen Demand (COD)	mg/L	0	196	

of SCRM. Subsequently, we present several research studies on concrete in the following paragraphs.

Knoeri et al. (2013) analyzed 12 types of recycled concrete (RC) and compared them with conventional concrete for three structural uses. RC showed about 30% environmental advantages primarily due to avoided burdens from steel recycling and waste disposal. However, differences in global warming potential (GWP) were more balanced, mainly influenced by additional cement requirements for RC. Pavlů et al. (2023) studied the LCA of a concrete slab produced from recycled aggregate concrete with sand. They compared ordinary reinforcement with steel bars and glass fibers. The outcomes indicate the positive environmental impact of replacing natural sand with a fine recycled aggregate. The decrease in climate change potential can be nearly 40% in some cases. Asadullahfardi et al. (2019) studied the environmental impacts of five concrete types using the LCA method. Geopolymer concrete had the lowest global warming effects, while OPC concrete was most environmentally friendly during production due to its lower environmental load due to its lowest level of environmental load. Manjunatha et al. (2021) applied LCA of concrete with three binding materials including OPC, ground granulated blast furnace slag (GGBS), and Portland pozzolana cement (PPC) using SimaPro 9.1 software and Ecoinvent database. Their outcome shows that PPC and GGBS have a superior impact on the environment once compared to OPC. Hottle et al. (2022) conducted LCAs for U.S. ready-mix concrete and Portland cement production. They found that advanced calcination tech reduces greenhouse gases, but also highlight significant metal and particulate matter (PM) emissions from non-combustion processes. Mostafaei et al. (2023) studied LCA and carbon footprint analysis of producing concrete and reinforcement concrete buildings from cradle to gate. The study includes extraction and production of raw materials for making concrete, in addition to concrete and rebar production, transportation of material, and delivery to construction workplace for reinforced concrete buildings. Backes et al. (2023) studied LCA a double wall of concrete with fiber using GaBi software.

They found the production of steel (blast furnace vs. electric arc furnace vs. recycled steel) and the selection of cement type are of key relevance. In addition, they concluded, that for concrete, a mixture of Portland cement and blast furnace slag is useful to pure Portland cement.

Table 5 Mixture proportions of SCRM

Sample code	W/C	Cement	MSWI fly ash	Sand	Fiber pp (%)	SP (%)
			kg/m^3			
M (0)	0.4	700	0	1223	0	0.72
M (C)	0.4	700	0	1223	0.1	1.03
FA5	0.4	665	35	1223	0.1	1.241
FA10	0.4	630	70	1223	0.1	1.284
FA20	0.4	560	140	1223	0.1	1.31
FAW5	0.4	665	35	1223	0.1	1.56
FAW10	0.4	630	70	1223	0.1	1.589
FAW20	0.4	560	140	1223	0.1	1.61

Utilizing SCRM for the restoration of concrete bridges and other structures is not just a case study; it represents a universally applicable solution for concrete repair worldwide. Furthermore, based on the authors' knowledge, there have been no instances where SCRM simultaneously incorporates wash water, MSWI fly ash, and PP fibers in its preparation. Another aspect to consider is that SCRM samples containing MSWI fly ash, wash water, and PP fibers have not been studied for their greenhouse gas emissions. Furthermore, the beneficial environmental impact of utilizing fly ash and wash water has not been examined.

In this study, we investigated the performance of SCRM incorporating MSWI fly ash and wash water. We determined the optimal admixture dosage and the maximum feasible amounts of MSWI fly ash, wash water, and PP fibers to achieve stable SCRM. Furthermore, we examined the impact of simultaneously using MSWI fly ash, wash water, and PP fibers in SCRM on both fresh and hardened concrete. Additionally, we conducted an LCA of several SCRM samples, focusing on global warming effect.

2 Materials and Methods

2.1 Materials

In this experimental program, Portland cement type 2 produced by Abyek Qazvin Cement Factory in Iran was utilized; the chemical characteristics are shown in Table 1, which are by ASTM C150 (2015) standard. Table 1 indicates the mechanical, and physical properties and the test method standards of Portland cement type 2. Fine aggregates used to produce the concrete samples were based on ASTM C136/136 M (2014). Figure. (1) shows the results of the sieve analysis of the fine aggregates. The aggregates were prepared from Meysam Mine in HashtGerd, Iran. The maximum size, water adsorption, and specific gravity of sand were 4.75 mm, 4.3%, and 2500 kg/m^3, respectively. Fly ash was used as a partial cement replacement additive. Table 2 presents the physical and chemical compositions of MSWI fly ash based on ASTM E 1621-13 (2013). Fig. (2) also presents the XRD results for MSWI fly ash. The fiber samples were prepared from the Clinical Concrete Company, Tehran, Iran. Table 3 illustrates the characteristics of fiber (Provided by the manufacturer). Wash water from the Aptus ready-mixed concrete plant in Alborz province was collected to produce SCRMs samples. When preparing SCRM, a larger amount of cement is necessary. Due to its fine-grained nature, cement contributes to increased shrinkage as the fine-grain content in the mortar rises. Consequently, shrinkage becomes a significant concern. SCRM lacking PP fibers tends to exhibit greater shrinkage, whereas the inclusion of PP fibers mitigates shrinkage while concurrently enhancing compressive strength (Saiz-Martinez et al., 2018).

Tap water was provided by the Alborz Provincial Water Authority. The wash water from washing the drum of concrete trucks at Aptus Concrete Batching Plant, located in Alborz province, Iran, was prepared. Table 4 provides the results of tap and wash water's physical and chemical properties. The wash water satisfies the ASTM C94-09 (2003) standard. Superplasticizer helps to reduce the need for water in concrete to achieve a lower water-to-cement ratio and thus reduce the cement content in concrete and maintain the desired concrete performance. A type of superplasticizer (SP) based on modified polycarboxylic acid copolymers was used for workability. Its specifications are liquid, iconic, light brown, specific gravity of 1.09 ± 0.02 kg/L, and maximum chloride content of 500 mg/L.

2.2 Mix Proportioning Methodology

Initially, efforts were made to achieve the initial mixture design without the inclusion of fiber and MSWI fly ash, recognizing that the inclusion of fibers results in a decrease in mini-slump flow. Consequently, it was determined that the mixture should aim to produce a maximum mini-slump as possible to achieve SCRM. After trial and error, the optimal initial mixing plan was obtained. To reach the optimal amount of fiber needed for the experiment, the amount of 0.1, 0.3, and 0.5% volume percent of cement was used. The experiments showed that using 0.5% of fiber by adding the permitted amount of superplasticizer leads to zero slumps; also, using 0.3% of fiber caused significant slump and bleeding, and only in 0.1% fiber a SCRM obtained, which was used for the samples.

For making SCRM sample, we weighed the sand, MSWI fly ash, tap water, superplasticizer, and Portland cement type 2 according to the mixing design for a 60-l concrete mixer. We poured these materials into the mixer and mixed them until the SCRM reached the desired consistency. Next, we gradually added the weighed PP fibers into the concrete mixer and thoroughly mixed them. As the mortar was prepared, air bubbles became visible on the surface, indicating the release of air from the SCRM. No segregation or clumping of PP fibers in the mortar was observed.

Eight types of SCRMs samples were selected. M (0) and M (C) denote control samples. Table 5 indicates the characteristics of all types of SCRMs. All samples were made and maintained at ambient temperature and 65 percent humidity. A 3-l mixer with a constant speed of 285 rpm was used for sample production. To make the mortar, water, superplasticizer, and cement were added first and were mixed for 30 s. The sand was then added, and the

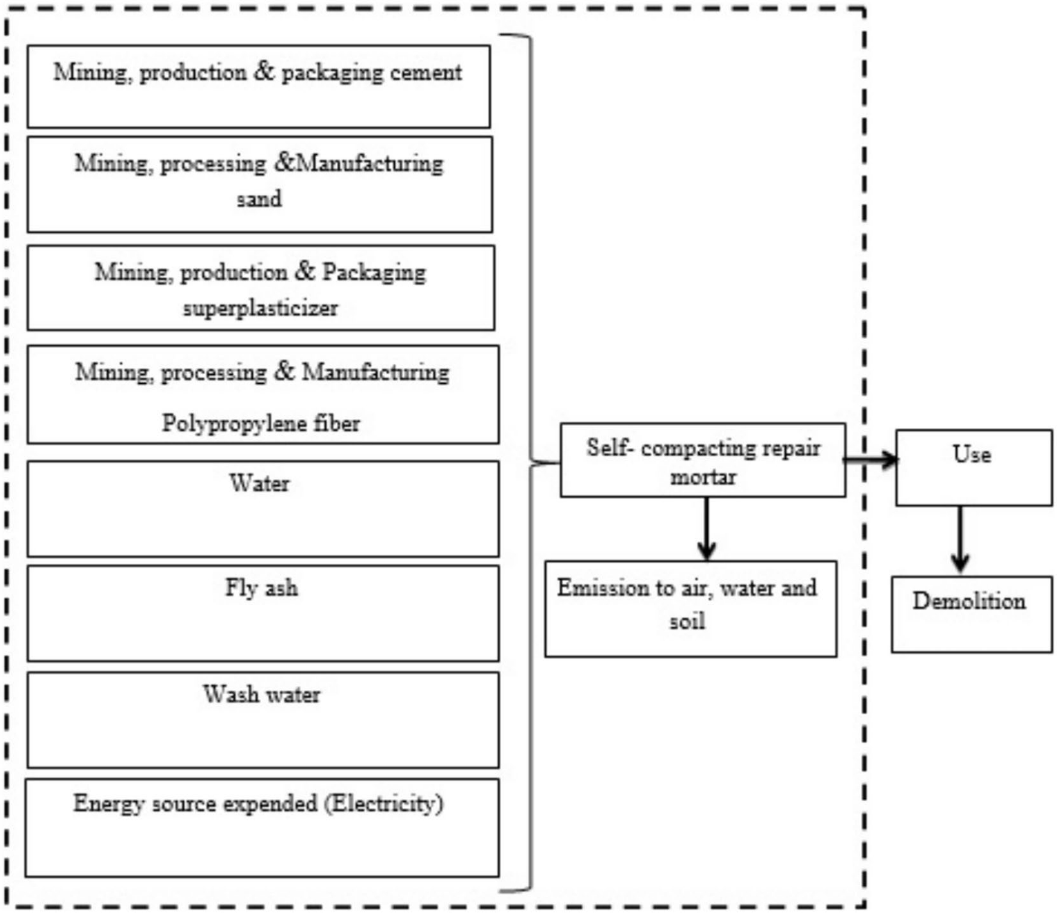

Fig. 3 The boundary of the life cycle system of four mortar production scenarios

mixture was continued for 30 more seconds. After fabrication, all samples were maintained in tap water for 7, 28, and 90 days for curing.

2.3 Test Methods

2.3.1 Fresh State

Mini-slump: The mini-slump assessed the workability of the samples, according to ASTM C143 (2004); this test was used to evaluate the flowability of fresh mortar under its weight.

Visual Stability Index (VSI): VSI was determined immediately after making SCRM and was used to present the mortar quality. To express this index, a number between 0 and 3 is assigned to the surface of the mortar. The zero for the sample is declared as entirely stable, one and two as stable and unstable, respectively, and three as completely unstable.

2.3.2 Hardened State

Compressive strength: The compressive strength of the concretes was determined at 7, 28, and 90 days, according to ASTMC109/C109M (2001). Three specimens were tested for each mixed design and age, and mean values were adopted.

Flexural strength test: The test is performed according to ASTMC348-02 (2002). For the flexural strength test at the age of 28 days for beam specimens (160 × 40 × 40 mm), the samples were placed horizontally inside the device on two supports, and a force was applied until failure.

UPV: An UPV test was done for SCRM samples at age 28 days, according to ASTM C 597-16 (2016). This test was used to study the mortar's quality and estimate the compressive strength in a non-destructive method.

Fracture toughness: According to Ayatollahi and Akbardoost's (2012) study, fracture toughness was performed. They developed Eq. 1 to determine the fracture toughness:

$$K_{IC} = \sigma_N \sqrt{2\pi \frac{w}{1000}} A_1^* \quad (1)$$

where K_{IC} is the fracture toughness, σ_N is nominal stress obtained from Eq. 2, w is the width of the specimen, and A_1^* is a non-dimensional parameter which depends on the geometrical ratios and loading conditions and is independent of specimen dimensions and magnitude of load. For the tested specimens, this dimensionless parameter is obtained from Eq. 3:

$$\sigma_N = \frac{3P_f S}{2tw^2} \quad (2)$$

where P_f is the fracture load, S is the loading span and t is the thickness of the specimen, respectively:

$$A_1^*(\alpha) = \frac{\sqrt{\alpha}(1.9 + 0.41\alpha + 0.51\alpha^2 - 0.17\alpha^3)}{\sqrt{2\pi}(1-\alpha)^{\frac{3}{2}}(1+3\alpha)} \quad (3)$$

where α is the crack length ratio, i.e., a/w.

2.4 Life Cycle Assessment (LCA)

Based on the requirements of ISO 14040 (2006), environmental LCA includes four stages: defining the objective and scope of the study, inventory of the life cycle, assessing the impacts, and finally interpreting the results.

2.5 Goal and Scope of the Study (ISO, 14041, 1998)

The main goal of this section is to compare the environmental emissions resulting from the LCA of 4 different types of SCRM including M (0), M (C), FA20, and FAW20. In this assessment, the operating unit was considered to produce 1 cubic meter of SCRM. The LCA was carried out by the cradle-to-gate method and with a process approach method. Fig. (3) indicates the system boundaries for the four target scenarios including extraction of raw materials and production of raw materials, transportation of raw materials to the workshop, and producing mortar in the workshop.

2.6 Life Cycle Inventory (ISO, 14041, 1998)

The Life Cycle Inventory (LCI) of SCRM production was compiled with the help of proper databases (such as Eco invent and EU and dk input–output database), queries from experts and valid research in this field were collected and entered into the SimPro software 9.5.

For the environmental burden caused by the production of by-products in the industry, such as MSWI fly ash and wash water from the ready-mixed concrete truck, due to the lack of further processing before the production of mortar, according to the principles of ISO 14044 (2006), no allocation is made (Tukenmez, 2019). In addition, the landfill site required for burying the MSWI fly ash and wash water from ready-mixed concrete truck needs treating before discharge to surface or groundwater. They are considered as avoided processes. Environmental burdens for the production of industry by-products such as MSWI fly ash and wash water were excluded by system expansion since further processing is not required for these materials before SCRM

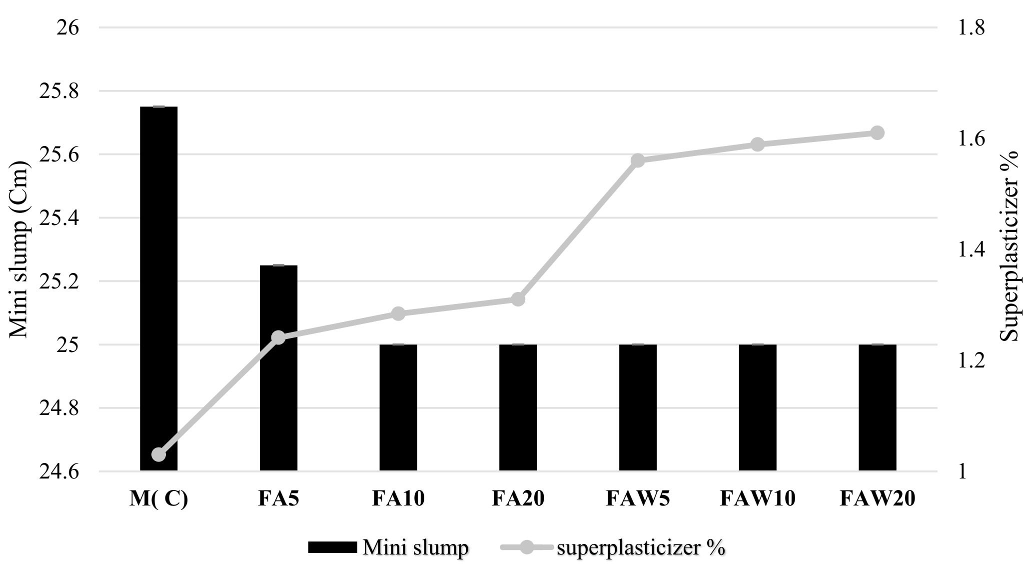

Fig. 4 Mini-slump and amount of superplasticizer of SCRM samples

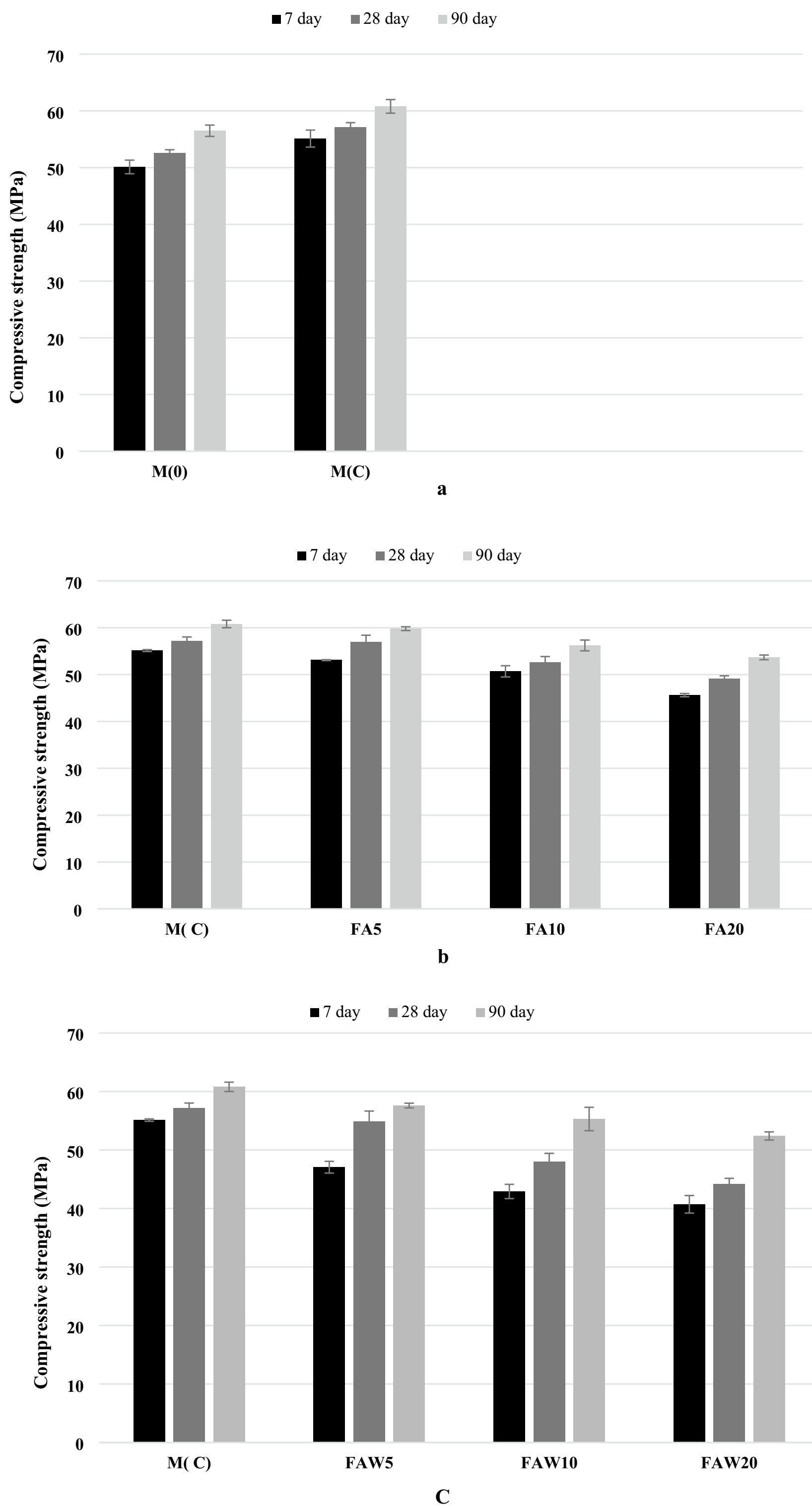

Fig. 5 The compressive strength results of SCRM for various mixture designs **a**) M(0), M(C) samples **b**) M(C) ,FA5, FA10, FA20 samples M(C), FAW5, FAW10, FAW20 samples

manufacturing and allocation is not applied in the scope of study as per ISO 14044 (2006).

In addition, landfill requirements and wastewater treatment for these materials were considered as avoided processes and introduced into the system model for mortar mixtures.

2.7 Superplasticizers (SPs)

Since there is only one type of SPs of formaldehyde type in the Ecoivent (3) database of Sima Pro software 9.5, and on the other hand, the purpose of this study was to compare four types of SCRM with a similar type of SPs; therefore, the same database was used in this study. The weight SPs were calculated by multiplying the amount of cement by the weight percentage of SPs (See Table 5).

– Electrical Energy Consumption

The cement mortar mixer was considered to have a volume of 3 L and a power of 200 watts per hour. The duration of using the mixer for each mixing plan was 2.5 min. Therefore, the power consumption of the mixer was considered to be 0.008 kW for all mixing designs.

– Transporting Raw Materials to the Workshop

Transporting raw materials to the SCRM production workshop, including transport distance, the type of truck, and the type of fuel consumption, we selected trucks with a capacity of 16 to 32 tons with Euro 3 fuel. The transportation distance for all materials was considered to be 30 km.

– Polypropylene Fibers

Yin (2015) computed the LCA of polypropylene fiber production (from extracting raw materials to transporting the produced fibers to the factory gate) and reported that the production of every 40 kg of polypropylene fiber produces 137 kg of equivalent carbon dioxide, which is about 60 kg is related to the production of fibers, and the rest is related to the production of polypropylene granules. Considering that there is only a polypropylene granule production process in Sima Pro software 9.5, modeling polypropylene fiber production and the amount of equivalent carbon dioxide released during the production process according to Yin's study for each kilogram of polypropylene fiber, 3.425 kg of carbon dioxide equivalent was considered.

It is worth mentioning that the production process of each kilogram of polypropylene granules in the SimaPro software also releases about 1.88 kg of equivalent carbon dioxide, which is acceptable with the results of Yin's study (in this study, the production of each kilogram of granules produces about 1.925 kg of carbon dioxide equivalent). The amount of polypropylene fiber for all scenarios was considered as a product of 0.1% density of polypropylene (0.91 g/cm^3) equal to 0.91 kg/m^3 of SCRM.

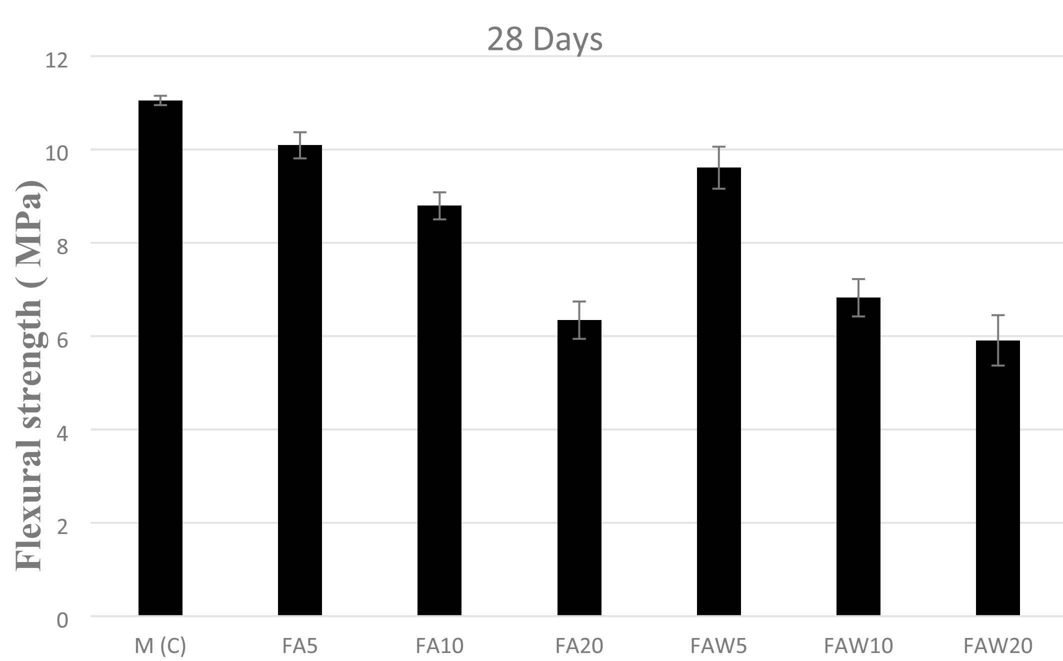

Fig. 6 The flexural strength of different SCRM designs using MSWI fly ash, tap water, wash water, and propylene fiber

2.8 LCA and Sensitivity Analysis

The LCA method in the present work was the IPCC 2021 GWP 100 method for measuring the impact of global warming. In addition, due to the lack of proper information in Iran; the Ecoinvent 3.6 database of SimaPro 9.5 software was used. Sensitivity analysis is performed to investigate the effect of special assumptions on the evaluation results and to find the parameters that have a greater contribution to the evaluation result. These parameters should be checked and corrected if necessary because changing their amount can have important impacts on reducing environmental pollution (Eriksson, 2012). The allocation method and evaluation method were subjected to sensitivity analysis in this study.

3 Results and Discussion

3.1 Mini-slump

The flowability of the SCRM was studied according to EFNARC (2002) to analyze the flow spread, and the flow rate conducted with a mini-slump cone. A minimum and maximum mini-slump value was set as 240 to 280 mm (EFNARC, 2002). Increasing the amount of MSWI fly ash and wash water caused the mini-slump in the SCRM samples to decrease. For this purpose, the amount of SPs was changed in each series of mixing to reach the set range for mini-slump. Obviously, with the increase in the amount of MSWI fly ash and wash water, the amount of SPs also increases. Using treated industrial wastewater and MSWI fly ash in SCC indicated the same results (Taherlou et al. 2021). Increasing MSWI fly ash can raise SPs and negatively affect workability due to dissolved solids in wastewater (Taherlou et al. 2021). As indicated in Fig. (4), to keep the mini-slump to a fixed rate (250 mm), the amount of SPs increased, and the maximum amount belongs to FAW20, which contains propylene fiber, MSWI fly ash, and wash water. However, the amount of SPs was according to EFNARC (2002)].

3.2 Compressive Strength

Since the composition of some MSWI fly ash has high CaO and albite compared to Portland cement, its use can reduce compressive strength. Figure. (5a–c) shows the average compressive strength of SCRM samples after 7, 28, and 90 days of curing, respectively. Considering Fig. (5a), it is clear that adding polypropylene fiber enhances the compressive strength of M (C) of the sample associated with a sample without fiber M (0). Fig. (5b) indicates that adding MSWI fly ash hurts the compressive strength of concrete and reduces its compressive strength. By raising the percentage of MSWI fly ash, this reduction is more significant. On the other hand, increasing the curing time increases the compressive strength in the long term. In addition, similar results were observed when MSWI fly ash and wash water were used in concrete. As Fig. (5c) shows, simultaneous use had a more negative effect on the samples; therefore, increasing the MSWI fly ash with wash water reduces the compressive strength by about 14% compared to the control sample (M (C)). The compressive strength of the samples indicated that the samples containing 20% MSWI fly ash made with wash water (FAW20) had the minimum compressive strength in the three investigated curing times. In contrast, the control sample (M (C)) has the highest compressive strength of 7, 28, and 90 days. While the results of Vaičienė and Simanavičius (2022) indicated that using MSWIBA, within 7 days of curing, increases the compressive strength compared to the control sample. In addition, they announced that the reduction of the initial compressive strength of concrete using MSWIBA could be due to the delay in cement hydration and lack of

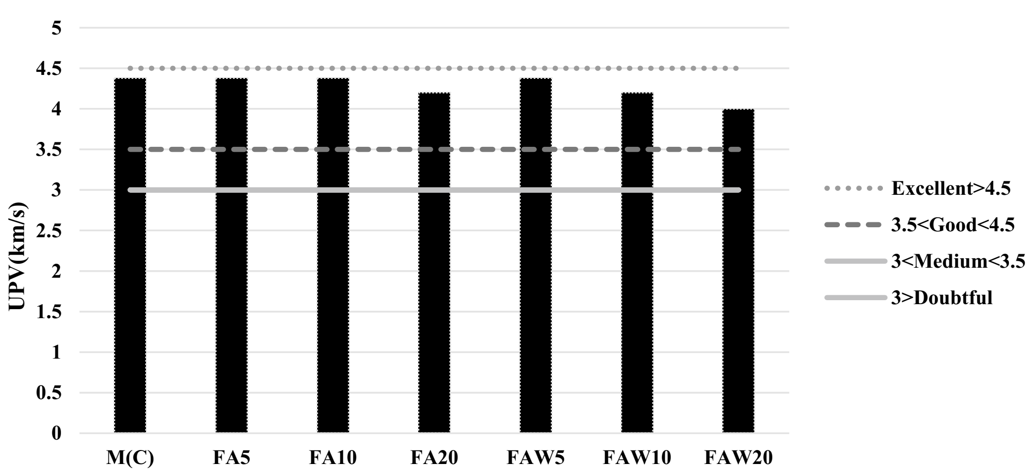

Fig. 7 UPV of different types of SCRMs designs using MSWI fly ash, tap water, wash water, and propylene fiber

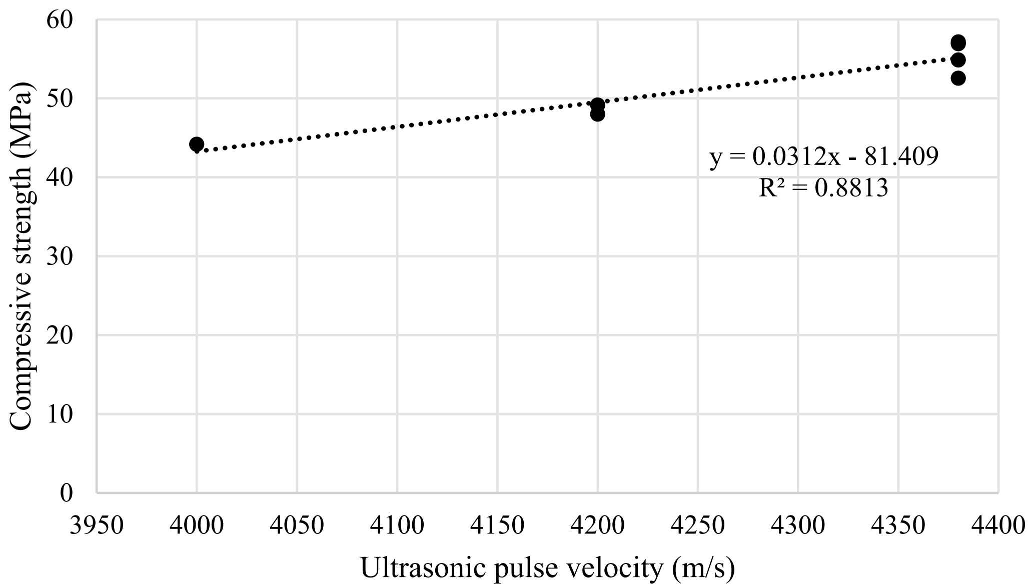

Fig. 8 Correlation between UPV and compressive strength of SCRM samples

proper development of CaO in cement compositions. In the study of Taherlou et al. (2021), they used MSWIBA and treated industrial wastewater instead of tap water in SCC. The result described decreasing the compressive strength with increasing the MSWIBA percentage. Rübner et al. (2008) reported that MSWIBA has concrete-damaging components, for example, sulfates, chlorides, organic components, unnecessary amounts of fine particles, glass content, and aluminum. They create cracks and spalling in concrete in a very short period. Fig. (2), XRD, indicates aluminum, sulfate, and glasses in the MSWI fly ash. The difference between the present work and other studies is in SCRM samples, we consumed, PP fiber, MSWI fly ash, and wash water, concurrently.

3.3 Flexural Strength

Fig. (6) indicates the flexural strength of different SCRMs using MSWI fly ash, wash water, and fiber concurrently. According to Fig. (6), in FA5, FA10, and FA20 samples by increasing MSWI fly ash amounts in SCRM from 35 to 140 kg/m^3, the flexural strength decreased from 10 to 6.2 MPa. When wash water was used in SCRM, the flexural strength was reduced from 9.7 to 5.95 MPa. The results show that the consumption of wash water and MSWI fly ash in SCRM concurrently decreases flexural strength slightly compared to using tap water. Bie et al. (2016) consumed MSWI fly ash as part of cement and indicated increasing MSWI fly ash percentage reduced the flexural strength of mortar. Our results are similar to Bie et al.'s study; however, we used MSWI fly ash and consumed it as part of the cement. Mostafa Galal et al. (2021) studied the flexural strength of mortar using wash water. They concluded that wash water decreased flexural strength slightly compared to using tap water. Asadollhfardi et al. (2022) also reached the same results of flexural strength as present work about normal concrete. Our results are in agreement with their studies. However, in the present work, we used MSWI fly ash, PP fiber, and wash water concurrently, which is different from other researchers.

3.4 Ultrasonic Pulse Velocity (UPV)

The UPV is associated with the density and integrity of the SCRM samples. Development of cracks and flaws inside SCRMs mortar samples together with disintegration decrease the UPV. Consequently, a periodic UPV quantity can reflect the variations that happen inside specific SCRM samples. These variations can be owing to the hydration of cement that increases the density and UPV or the progress of internal cracks and disintegration owing to any worsening mechanism, which decreases the UPV (Mirvalad & Nokken, 2015).

Karaiskos et al. (2015) stated that if UPV is bigger than 4.5 km/s, the quality of concrete is excellent. Subsequently, If UPV is between 3.5 and 4.5 km/s, the concrete quality is good. Furthermore, if UPV is between 3 and 3.5 km/s, the quality of concrete is medium, Lastly, when UPV is less than 3 km/s, the concrete quality is doubtful.

Figure. (7) presents the UPV of different types of SCRM designs using MSWI fly ash, tap water, wash water, and PP fiber. As indicated in Figure. (7), UPV of all different SCRM designs ≥ 4. It means the SCRMs with

Table 6 The results of fracture toughness of different SCRM mixture designs

Codes	No	Crack length *a* (mm)	Samples width *w* (mm)	$\alpha = a/w$	Samples thickness *t* (mm)	Span length S(mm)	Fracture load P_f (N)	Nominal stress σ_N (MPa)	A_1*	Fracture toughness K_{IC} (MPa.$\sqrt{m}$)	Ave
M(C)	1	16.92	39.74	0.4257	42.12	120	763.22	2.065	0.565	0.583	0.6726
	2	17.62	39.21	0.4493	41.80	120	814.34	2.280	0.605	0.685	
	3	17.6	39.6	0.444	39.88	120	873.66	2.514	0.596	0.748	
FA5	4	17.25	40.97	0.4210	41.01	120	896.72	2.345	0.558	0.6684	0.6559
	5	17.76	40.6	0.4374	41.17	120	862.19	2.287	0.585	0.6756	
	6	17.26	40.61	0.4250	40.82	120	810.43	2.167	0.565	0.6237	
FA10	7	17.32	40.12	0.4317	41.14	120	768.13	2.088	0.576	0.6032	0.6390
	8	17.52	40.3	0.4347	41.02	120	852.63	2.304	0.581	0.6728	
	9	17.31	41.15	0.4207	41.57	120	884.05	2.261	0.558	0.6411	
FA20	10	17.87	40.51	0.4411	42.57	120	735.11	1.894	0.591	0.5648	0.5472
	11	17.68	39.62	0.4462	42.4	120	693.97	1.877	0.600	0.5617	
	12	17.33	39.59	0.4377	42.4	120	651.28	1.764	0.586	0.5150	
FAW5	13	17.75	39.5	0.4494	40.31	120	694.20	1.987	0.606	0.5992	0.5791
	14	16.85	41	0.4110	41.6	120	792.76	2.041	0.543	0.5623	
	15	16.85	41	0.4110	41.2	120	868.58	2.257	0.543	0.5760	
FAW10	16	18.31	41.19	0.4445	42.44	120	764.79	1.912	0.597	0.5806	0.5766
	17	17.62	39.21	0.4494	41.8	120	682.03	1.910	0.606	0.5740	
	18	18.24	40.9	0.4460	42.11	120	740.67	1.893	0.600	0.5751	
FAW20	19	16.97	43.14	0.3934	39.44	120	793.17	1.945	0.517	0.5239	0.4844
	20	16.57	40.39	0.4103	43.27	120	662.06	1.688	0.542	0.4608	
	21	18.42	39.56	0.4656	42.79	120	550.39	1.479	0.635	0.4684	

Table 7 Global warming potential (GWP) of four different SCRM using Simapro 9.5 software and the IPCC 2021 GWP 100 method

Impact category	Unit	M0	MC	FA20	FAW20
GWP100	kg CO_2-eq	667.7087	673.6931	544.753	546.0439

Table 8 The results of the environmental LCA of four SCRM production scenarios using the IPCC 2021 GWP 100 method considering avoided products

Environmental impact	Unit	M0	MC	FA20	FAW20
GWP100	kg CO_2-eq	667.7087	673.6931	535.6383	− 201.5670

different mixture designs are of good quality. The UPV of FA20 and FAW20 samples are slightly less than other SCRMs mixture designs. This experiment, together with the compressive strength test can indicate the integrity of mortar samples.

Saxena and Tembhurker (2018) concluded that UPV decreased by 4–9% when wastewater was consumed in concrete compared to the control sample. Asadollahfardi et al. (2022) used treated domestic wastewater and waste foundry sand in normal concrete. They found that treated domestic wastewater reduced UPV on normal concrete. Our results are in line with their results. However, we used MSWI fly ash, wash water, and PP fibers in SCRM samples.

Fig. (8) indicates the correlation between UPV and compressive strength. As indicated in Fig. (8), there is a high correlation coefficient ($R^2=0.8813$) between UPV and compressive strength.

Investigating compressive strength along with UPV has been done by other scholars (Mirvalad & Nokken, 2015).

The higher the compressive strength of the mortar indicates the fewer voids in the specimen (Widodo et al., 2022).

The outcome indicated that UPV results are straight proportional to the compressive strength of the SCRMs. In addition, as reported by Widodo et al. (2022) is in reverse to compare to the porosity.

Table 6 presents the results of fracture toughness of different SCRM mixture designs. According to Table 6,

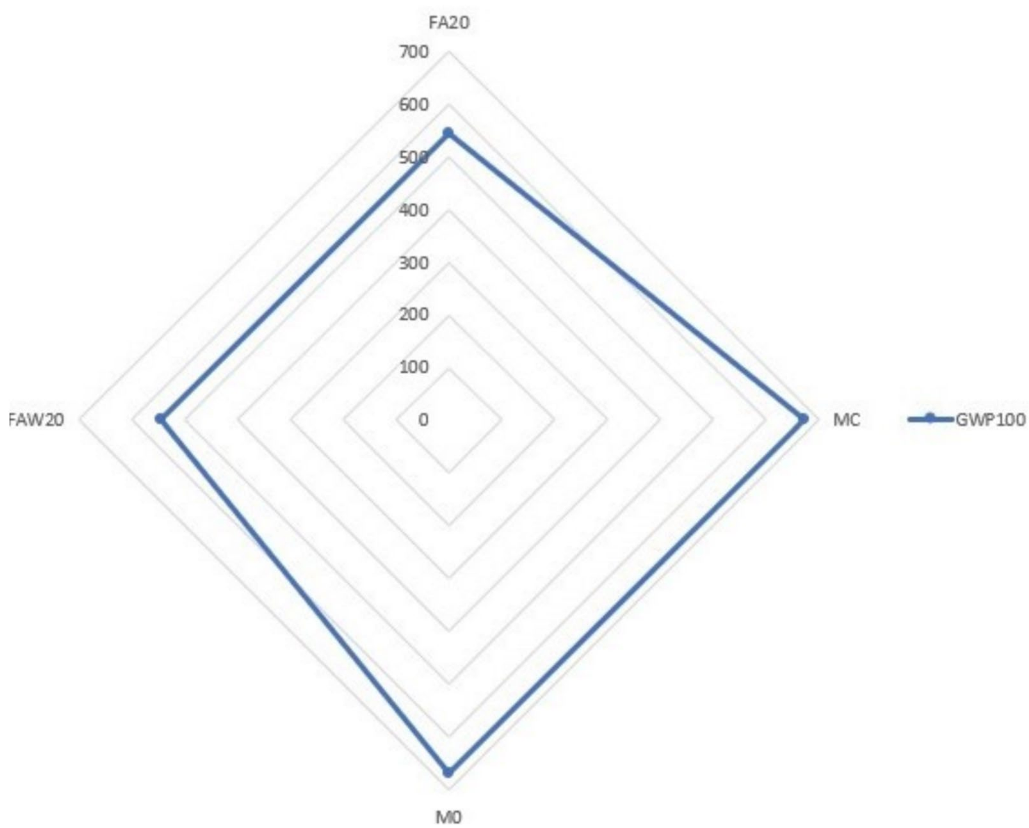

Fig. 9 A comparison of the results of global warming potential (GWP) of four different SCRM samples

Table 9 The evaluation results of SCRM samples separately for each item

Damage category	Unit	Total	Cement	Tap water	Sand	SPs	Polypropylene Fiber	Transporting cement	Transporting sand	Transporting superplasticizer	Transporting	Packing, cement	Electricity
M0	kg CO_2-eq	667.71	638.72	0.35	5.22	6.62	0.00	4.04	7.07	0.03	0.00	5.65	0.01
MC	kg CO_2-eq	673.69	638.72	0.35	5.22	9.47	3.12	4.04	7.07	0.04	0.01	5.65	0.01
FA20	kg CO_2-eq	544.18	510.98	0.35	5.22	9.63	3.12	3.24	7.07	0.04	0.01	4.52	0.01
FAW20	kg CO_2-eq	546.04	510.98	0.00	5.22	11.84	3.12	3.24	7.07	0.05	0.01	4.52	0.01

Table 10 The comparison of the results of four methods to determine GWP of four types of SCRM samples

Environmental Impact	Unit	M0	MC	FA20	FAW20
GWP100	kg CO_2-eq	667. 71	673.69	544.17	546.04
Climate change, short-term (IMPACT)	kg CO_2 eq	674.72	680.80	549.97	551.90
Difference (%)	− 1.07	− 1.050	− 1.07	− 1.07	− 1.05
Global warming (ReCipe)	kg CO_2 eq	674.61	680.68	549.88	551.811
Difference (%)	− 1.05	− 1.040	− 1.050	− 1.06	− 1.03
Global warming (BESS)	kg CO_2 eq	659.92	665.80	537.7327	539.53
Difference (%)	1.18	1. 17	1.18	1.19	1.17

adding MSWI fly ash to the SCRM samples reduces fracture toughness. In addition, increasing MSWI fly ash % to SCRM sample caused to decrease in fracture toughness. Using wash water instead of drinking water and MSWI fly ash % concurrently in SCRM decreased more fracture toughness of SCRM samples compared to using only MSWI fly ash and drinking water in SCRM samples. Both MSWI fly ash and wash water have negative effects on the fracture toughness of SCRM. Peighambarzadeh et al. (2020) used treated domestic wastewater for normal concrete, and they indicated decreasing fracture toughness by up to 6%. Niu et al. (2022) [72] studied the effect of municipal solid-waste inclinator ash (MFA) on MFA-geopolymer concrete (GC). They concluded that increasing the amount of MFA in MFA-GC caused decreasing fracture toughness.

3.5 LCA Results

Table 7 indicates the results of global warming potential (GWP) of four different SCRM using SimaPro 9.5 software and the IPCC 2021 GWP 100 method.

As shown in Table 7, the SCRM sample utilizing MSWI fly ash (FA20 sample) resulted in 544.753 kg of CO_2 equivalent, the SCRM sample incorporating MSWI fly ash and wash water (FAW20 sample) yielded 546.0439 kg of CO_2 equivalent, the SCRM sample without PP fibers and MSWI fly ash (M0) generated 667.7087 kg of CO_2 equivalent, and the SCRM sample with polypropylene fibers (MC) produced 673.6931 kg of CO_2 equivalent in GWP potential. This indicates that incorporating MSWI fly ash and wash water into SCRM, as observed in the FAW20 sample, reduces GWP100 compared to the M0 sample. Figure. (9) also compares the results of GWP for four different SCRM samples, confirming that the utilization of MSWI fly ash and wash water in SCRM is beneficial for environmental sustainability.

It is worth mentioning that in this work, the by-products produced in other processes (MSWI fly and wash water) were considered with zero environmental burden. If we include the positive environmental burden due to the use of these products in the calculation (no need to build a landfill for burying the incinerator fly ash and no need to treat the wash water from ready-mixed concrete truck washing), the results will be as illustrated in Table 8.

As presented in Table 8, the use of wash water from ready-mixed concrete trucks and MSWI fly ash can reduce the environmental burden of SCRM production to − 201,567 kg CO_2-eq, which indicates the production of an environmental advantage. Table 9 presents the evaluation results of SCRM separately for each item.

Considering Table 9, the amount of *SPs* consumption has a great impact on the production of equivalent CO_2 after cement usage because despite the use of concrete truck wash water in FAW20 of SCRM sample and avoiding calculating the environmental burden of producing and treatment and transporting drinking water to prepare cement mortar, the environmental burden of this mortar is not much different from FA20 sample prepared from drinking water. In addition, the use of PP fibers increased the environmental load of the MC sample compared to the M0 sample without fiber.

The results indicate that incorporating MSWI fly ash while reducing cement consumption in SCRM samples (refer to Table 5), and substituting wash water for drinking water, even with the additional consumption of SPs, can reduce the GWP impact by 127 kg of CO_2 equivalent.

The consumption of cement in the production of SCRM samples produced the largest amount of carbon dioxide. As shown in Table 9, the consumption of 700 kg/m^3 (see Table 5) of cement produced 638.72 kg CO_2-eq. which by reducing the amount of consumption to 560 kg/m^3 (see Table 5) and replacing it with MSWI fly ash in FA20 and FAW20 samples, the GWP reduces to 510.98 kg CO_2-eq. The consumption of SPs is ranked second in the GWP, and considering the FAW20 sample with the generation of 11.84 kg CO_2-eq., FA20 sample with 9.63 kg CO_2-eq., MC sample with 9.47 kg CO_2-eq., and M0 sample with of 6.62 kg CO_2-eq. produced the highest to the lowest amount of GWP. The transportation of 1223 kg of sand with the generation of 7.07 kg CO_2-eq. ranks third in GWP generation. Packing 700 kg of cement produces 5.65 kg CO_2-eq; transporting it generates 4.04 kg CO_2-eq., and packing 560 kg of cement produces 4.52 kg CO_2-eq., and transporting it generates 3.24 kg CO_2-eq. The consumption of 1223 kg of sand with the production of 5.22 kg CO_2-eq. per ton of SCRM production is in the fifth position of GWP. Consumption of 280 kg of drinking water has produced 0.35 kg CO_2-eq. per cubic meter SCRM production. Transportation of SPs and PP fibers, as well as electricity consumption for SCRM production, with 0.05 to 0.01 kg CO_2-eq., also reaches the least impact on GWP.

Ecoivent database 3.6 offers two allocation system models, including the cutoff method and the consequential system. In the present work, the cutoff method was used based on the determined objective. According to Yin's study, choosing any of these methods does not have a significant effect on the evaluation result (Yin, 2015); therefore, the result of this study is not sensitive to the selected method. In addition, the assessment was carried out with three other methods of LCA. Table 10 illustrates the comparison of the results of four methods to determine global GWP of four types of SCRM samples.

As indicated in Table 10, the comparison of four different methods of LCA for the computation of GWP have negligible differences (− 1 to 1.2%). Therefore, the evaluation results do not depend on the chosen method.

4 Conclusions

The present work includes experimental works using different percent of MSWI fly ash, PP fiber, and wash water concurrently in SCRM to determine workability and mechanical properties. In addition, GWP was analyzed using LCA. The summary of the key results is as follows:

1- Increasing the parentage of MSWI fly ash and using wash water in SCRM caused the mini-slump decreases and enhancement of MSWI fly ash can increase superplasticizer and undesirably affect workability.
2- Incorporating PP fiber into SCRM enhances its compressive strength compared to samples without fiber. Increasing the content of MSWI fly ash in SCRM decreases compressive strength when using drinking water, and samples containing 20% MSWI fly ash produced with wash water reached the minimum compressive strength at three different curing times.
3- When concurrently using MSWI fly ash and wash water in SCRM compared to using MSWI fly ash, compressive strength decreased slightly. By increasing MSWI fly ash from 35 to 140 kg/m^3 and reducing the same amount of cement in SCRM, the flexural strength decreased from 10 to 6.2 MPa.
4- The UPV of different SCRM samples is between 4 and 4.5 km/s, which shows a proper range. Similarly, there is a good correlation between compressive strength and UPV of all SCRM samples.
5- Adding MSWI fly ash % to SCRM samples caused to reduction in fracture toughness. The usage of wash water in place of drinking water and MSWI fly ash % simultaneously in SCRM decreased fracture toughness compared to the usage of MSWI fly ash and drinking water.
6- The minimum global warming is generated using MSWI fly ash in the SCRM sample, and the maximum belongs to samples using drinking water and PP fibers. It means that using wash water and MSWI fly ash in SCRM samples reduces global warming potential sharply.
7- Considering avoided products using the IPCC 2021 GWP 100 technique, consumption of wash water from ready-mixed concrete trucks can decrease the environmental burden of SCRM production to − 201,567 kg CO_2-eq., which shows the production of an environmental benefit.

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Author contributions
Material preparation, data collection, and experimentation were conducted by Ehsan Abdi. The life cycle assessment analysis was carried out by Azadeh Panahandeh. The initial draft of the manuscript was written by Gholamreza Asadollahfardi and Negar Esmaeili. Supervision of experimental work in the laboratory was overseen by Amirmasoud Salehi and Javad Akbardoost. Gholamreza Asadollahfardi was responsible for suggesting the study proposal, as well as reviewing and editing both the initial and final draft.

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Availability of data and materials
The data are available whenever the journal require.

Declarations

Ethics approval and consent to participate
This is not applicable for my study. All the authors give informed consent to participate in the study.

Consent for publication
All the authors have unanimously agreed with the content and have explicitly provided consent for the publication of their data in the paper submitted to the Journal of Concrete Structures and Materials.

Competing interests
We, the author's team, certify that we have no affiliations with or involvement in any organization or entity with any financial interest (including honoraria, educational grants, participation in speakers' bureaus, membership, employment, consultancies, stock ownership, or other equity interest, and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

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