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SELF-COMPACTING CONCRETE STRENGTHENING EFFICIENCY INVESTIGATION USING RECYCLED STEEL WASTE AS FIBRES

Key words: self-compacting concrete, waste steel fibre, compressive strength, recycling material, splitting tensile strength, adding recycled material

Introduction

There has been increased focus in recent years on recycling industrial manufacturing waste due to the massive amounts of pollution that is predicted as a result of industrial operations and its detrimental impact on the environment.

In general, there have been many studies on reusing waste material in concrete, such as carpet waste, used tires, polypropylene and nylon, wood fibre as paper product waste, steel shavings as an alternative to steel fibres (Wang, Wu & Li, 2000), and iron waste (Ghannam, Najm & Vasconez, 2016) to benefit from waste material while improving the properties and performance and lowering costs by including the recycled fibre into the process as a substitute for manufactured fibres to avoid disposing of waste in landfills.

Steel fibres are commonly utilized in structural facilities as well as other applications. Slope stabilization is a term used to describe the process of making a slope more stable. Artificial fibres improve the efficiency of the concrete, but they are not without their drawbacks. Produced from non-renewable and expensive materials, the steel industry generates large quantities of steel waste materials, which can be environmentally damaging if left untreated (Merli, Preziosi, Acampara, Lucchetti & Petruci, 2020).

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The primary waste products from steel product manufacturing, which offer severe concerns across the world, may be reduced by using it as a resource, such as by turning machine recyclable materials into fibre for concrete. The use of certain wastes in concrete is considered a safe resource (Prasad, Maanvit, Jagarapu & Eluru, 2020).

Mohammadi, Singh and Kaushik (2008) discussed steel waste fibre as an admixture material in concrete, which was an appealing choice as steel waste has high strength and durability, which could lead to an increase in the strength of the concrete as well as improving some of its properties, such as ductility, impact resistance and dynamic load resistance, as well as delaying the evolution of macro cracks, especially their width.

Aghaee and Yazdi (2014) used waste steel wire from rebar and wooden moulds previously used in construction projects in lightweight structural concrete (SLWC) testing. To assess the mechanical characteristics of 28-day reinforced lightweight concrete samples using waste wire, a series of tensile, flexural, and impact tests were conducted. In the volume fraction of concrete, the percentage of wire in fibre-reinforced concrete was 0.25%, 0.5% and 0.75%. The findings show that concrete's bending, tensile, and impact characteristics may be significantly enhanced through the use of discarded wire. The use of scrap steel wire as a suitable fine reinforcement in lightweight concrete is also concluded.

In general, it is understood that fibre-reinforced concrete, which uses a variety of metallic, hybrid, and polymeric fibres, may enhance the behaviour of concrete when it has cracked by bridging the fractures, reducing the energy consumption and enhancing the ductility capacity of the concrete elements.

Jang and Yun (2018) investigated the effect of steel fibre content and coarse aggregate size on the mechanical properties of high strength concrete. The research also showed the relationship between compressive strength and bending strength of high strength steel fibre reinforced concrete (SFRC) used in four ratios: 0.5%, 1%, 1.5% and 2%. Compression and bending tests were performed, and the results were then used to verify the effect of the steel fibre volume fraction and the total volume on the SFRC's compressive, flexural and bending hardness, which increased significantly with increasing steel fibre ratio. Also, the equations that have been proposed to determine the compressive stiffness ratio based on the equivalent flexural strength ratio were used to predict the mechanical properties of SFRC in this study.

Orouji, Zahrai and Najaf (2021) added different quantities of glass fibre and polypropylene fibre to investigate their effect on the compression and flexural strength of lightweight concrete. The percentages of glass were 20%, 25% and 30%, while the percentages of used polypropylene fibres were 0.5%, 0.75%, 1%, 1.5% and 2%. The increase in the compressive strength, flexural strength, and ductility of the tested specimens were reached about 1.6, 4.0 and 13.2 times, respectively.

Najaf, Abbasi and Zahrai (2022) studied the effect of using waste glass powder, polypropylene fibres and microsilica to manufacture lightweight and sustainable concrete with high compressive and bending strength, ductility, and impact resistance.

The objective of this research was to investigate the efficiency of recycled steel scrap as a fibre on the mechanical characteristics of self-compacting concrete. The more highlighted goal was to evaluate the optimal amount and percentage of steel scrap and also to investigate the variation in the mechanical properties of concrete with time. As a result, more research is needed on the strength of concrete as well as how to estimate the best rates for adding recycled steel waste.

The goal of the study was to examine how effectively self-compacting concrete's mechanical properties can perform when recycled steel is used as a fibrous reinforcing material.

Experimental program

The implications were studied of adding steel waste on the mechanical characteristics of self-compacting concrete. Waste steel scrap was used as fibres to strengthen concrete. Compressive and splitting tensile strengths were the properties studied, as well as their effect on strength development over time. Slump test concrete workability diminishes according to the fraction of recycled steel scrap that is added (Sharma & Ahuja, 2015).

Materials specifications

Cement

Tables 1 and 2 illustrate the cement properties that were used to manufacture the concrete. Ordinary Portland cement was adopted. The physical characteristics of the cement were tested using the standards established by ASTM International (formerly known as American Society for Testing and Materials): ASTM C184-94e1 (2020b), ASTM C187-16 (2020c), ASTM C188-17 (2020d) and ASTM C19-19 (2020a).

TABLE 1. Chemical analysis of the cement

Chemical element	Test result [%]	Specification limit [%]
SiO_2	22.40	–
Al_2O_3	5.78	–
Fe_2O_3	3.24	–
CaO	66.55	–
MgO	3.98	≥ 5.0
SO_3	2.23	≥ 2.5
LOI	3.11	≥ 4.0
IR	0.98	0.66–1.02
C_3A	2.89	≥ 3.5

TABLE 2. Physical test results of cement

Test item	Test result	Specification limit
Initial setting [min]	112	≤ 45
Final setting [min]	334	≤ 600
Soundness expansion, le Chatelier [mm]	1.4	≤ 10
Compressive strength (3 day curing) [MPa]	15.39	≤ 15.00
Compressive strength (7 day curing) [MPa]	24.10	≤ 23.00

Sand

A fine aggregate, which was natural sand, had a fineness modulus of 2.65. The particles of sand larger than 4.75 mm were eliminated via sieve analysis (Table 3).

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TABLE 3. Test results of sand

Opening size [mm]	Passing [%]	Specification			
		A	B	C	D
9.5	100.00	100	100	100	100
4.75	98.99	90–100	90–100	85–100	95–100
2.36	89.22	60–95	75–100	85–100	95–100
1.18	75.68	30–70	55–90	75–100	90–100
0.6	53.88	34–15	35–59	60–79	80–100
0.3	17.79	20–5	8–30	12–40	15–50
0.15	3.01	0–10	0–10	0–10	0–10
SO_3	Test result	Specification			
	0.41%	< 0.50%			

Gravel

Crushed coarse aggregate was used, with a maximum size of 19 mm and a fineness modulus of 2.7. The gradation of the coarse aggregate's proportionate particle sizes was assessed by sieve analysis (Table 4).

Plasticizer

To avoid a negative effect, a superplasticizer was added to the concrete mix. The superplasticizer, SEKA 5390, conforms to the ASTM C494 standard (ASTM, 2012).

Steel waste

Steel fibres have a detrimental impact on workability; but despite this they improve the mechanical characteristics of concrete (Ulas, Alyamac & Ulucan, 2017).

As illustrated in Figure 1, discarded steel waste was selected for mixing purposes. Since waste steel scrap performs well as steel fibre in concrete, the aspect ratio (length to diameter) was set at 50–60 according to the ACI 544.3R-93 standard related to steel fibres (American Concrete Institution [ACI], 1993). The material qualities of the primary structural steel are passed down to the waste steel, and to meet this requirement the steel wastes were cut to a size that did not exceed 0.9525 cm (see Figure 1).

Poisson's ratio was 0.3, the modulus of elasticity was 200 MPa, and the relative density was 7,850 $kg \cdot m^{-3}$.

TABLE 4. Test results of gravel

Opening size [mm]	Passing [%]	Specification		
		5–40 [mm]	5–20 [mm]	5–14 [mm]
37.5	100.00	95–100	100	–
19.0	98.10	35–70	95–100	100
9.5	42.30	10–40	30–60	50–80
4.75	8.60	0–5	0–10	0–10
SO_3	Test result	Specification		
	0.41%	< 0.10%		

FIGURE 1. Technique for processing recycled steel fibre

FIGURE 2. Preparing samples groups for testing

Mix design

The mix design was carried out in accordance with the ACI 544.3R-93 standard (ACI, 1993). All material quantities are described in Table 5.

Specimen preparation

The work addressed three groups of concrete, labelled: Ws0, Ws1 and Ws1.5, which were without steel waste fibre addition (Ws0), with 1% steel waste fibre addition (Ws1), and with 1.5% steel waste fibre addition (Ws1.5).

Concrete samples were stored for 28 days in a water pool for curing. Figure 2 shows samples during preparation.

Experimental tests

Compressive strength test

To investigate the compressive strength of the concrete, standard cube specimens were used, with dimensions of 15 × 15 × 15 cm in accordance with the ACI 544.2R-89 standard (ACI, 1989). A uniaxial compression test was constructed. The compressive strength

TABLE 5. Quantity of materials for the designated concrete sample groups

Group	Cement [kg·m^{-3}]	Sand [kg·m^{-3}]	Crushed gravel [kg·m^{-3}]	w/c	Superplasticizer SEKA 5390 [%]	Steel waste fibre [%]
Ws0	380	750	1 024	0.38	0.8	0
Ws1	380	750	1 024	0.38	0.8	1.0
Ws1.5	380	750	1 024	0.38	0.8	1.5

of concrete grade C-30 was the intended result. Concrete with volumetric ratio of steel waste fibres was the variable. Three steel waste volumetric ratios were evaluated: 0%, 1% and 1.5%.

The compressive strength of the cube sample was calculated by the following equation:

$$f_{\text{comp.}} = \frac{P_C}{A}, \tag{1}$$

P_C – compression failure load [kN],
A – loaded area of cube [cm^2].

The compressive tests, as shown in Figure 3, were conducted after 7, 14 and 28 days of dipping in water for curing.

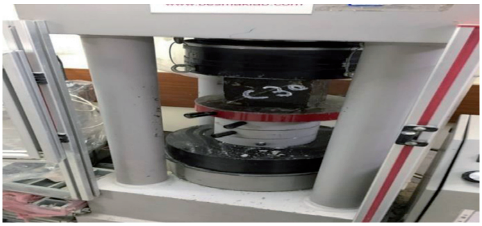

FIGURE 3. Compressive strength test

Tensile strength test

For tensile strength, sample cylinders with a diameter of 15 cm and a length of 30 cm all underwent splitting tests, with a target load of 1.2 $mPa \cdot s^{-1}$. The set up for the splitting test is shown in Figure 4. The test was run in accordance with the ASTM C496-86 standard (ASTM, 1986).

The compressive load of the cylinder sample was calculated by the following equation:

$$f_{\text{split.}} = \frac{2P}{\pi DL}, \tag{2}$$

P – compressive load [kN],
D – diameter of cylinder sample [cm],
L – length of cylinder sample [cm].

FIGURE 4. Splitting tensile test

Results

Compression strength

The compressive strengths from the samples tests are listed in Table 6, for the day 7, day 14 and day 28 samples for groups Ws0, Ws1 and Ws1.5. The average compressive strengths given in Figure 5 is for the day 14 samples. Figure 6 represented the average compressive strength at day 28.

The uniaxial compression test shows that the 1% steel waste increases in compressive strength on day 28 by 12% as a result of the bridging effect of the steel waste, where the cracks had difficulty in extending. The 1.5% steel waste only increased the compressive strength by 0.35% in comparison with the specimen without steel waste on day 28.

TABLE 6. Average compressive strength on days 7, 14 and 28, for the Ws0, Ws1, Ws1.5 sample groups

Group	Density [kg·m^{-3}]	Water content [%]	Average compressive strength on day 7 [MPa]	Average compressive strength on day 14 [MPa]	Average compressive strength on day 28 [MPa]
Ws0	2 350	144.4	30.68	36.56	43.83
Ws1	2 691	144.4	35.00	38.66	49.15
Ws1.5	2 788	144.4	30.80	40.00	44.00

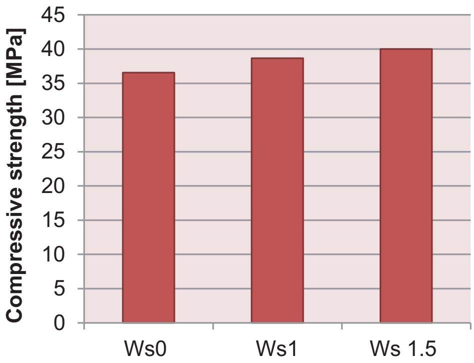

FIGURE 5. Average compressive strengths for samples groups Ws0, Ws1, Ws1.5 on curing day 14

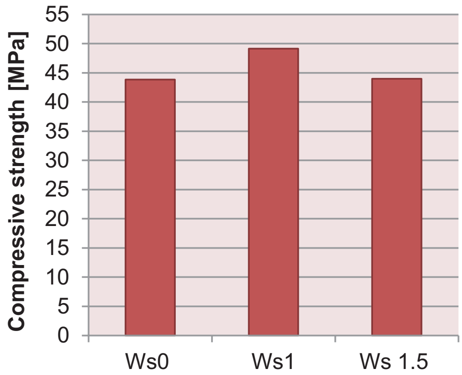

FIGURE 6. Average compressive strengths for samples groups Ws0, Ws1, Ws1.5 on curing day 28

The reason for the low difference in the compressive strength is that the low strength of concrete, corresponding to the high strength of steel fibres, causes severe spalling of the concrete around the splitting hole of the fibres. The results from the experiment are compiled in Table 6.

Tensile strength

The results of the tensile strength are given in Table 7 for days 7, 14 and 28 for groups Ws0, Ws1 and Ws1.5. The average tensile strength values are given in Figure 7 for day 14, the average Ws was 2.92, as well

TABLE 7. Average tensile strength on days 7, 14 and 28, for the Ws0, Ws1, Ws1.5 sample groups

Group	Average tensile strength on day 7 [MPa]	Average tensile strength on day 14 [MPa]	Average tensile strength on day 28 [MPa]
Ws0	2.23	2.92	3.18
Ws1	2.78	3.498	3.91
Ws1.5	2.87	3.63	4.10

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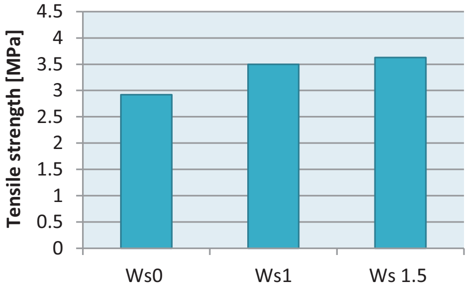

FIGURE 7. Average tensile strengths for sample groups Ws0, Ws1, Ws1.5 on day 14 of curing

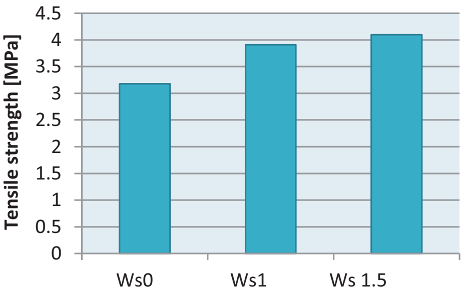

FIGURE 8. Average tensile strengths for sample groups Ws0, Ws1, Ws1.5 on day 28 of curing

as 3.5 and 3.63 for Ws1 and Ws1.5 respectively. The reason for this was the increased interlocking between the components of the concrete mixture by increasing the percentage of fibres in the concrete mixture, which in turn delayed the appearance of cracks and reduced their width. Fibres also have a major role in forming connecting bridges in the crack area to help increase endurance and create additional tensile resistance. While Figure 8 gives the average tensile strength at the day 28 point, which was 3.18, 3.91, and 4.1 for Ws0, Ws1 and Ws1.5, respectively.

Development of strength with age

Figure 9 illustrates the relationships between compressive strength development of the strength on days 0, 7, 14 and 28, and it was indicated that on day 14 the average strength of group Ws1 and Ws1.5 was more than group Ws0, without waste steel fibre, would achieve on day 28, with Ws1 achieving the highest value and Ws1.5 close to Ws0.

Figure 10 shows the relationship between tensile strength development and the strength on days 0, 7, 14 and 28, and it is indicated that on day 14 the average strength of group Ws1.5 achieved a value equal to the highest by Ws1, and this was also more than group Ws0, and it was also shown that Ws1.5 on day 28 achieved the highest value.

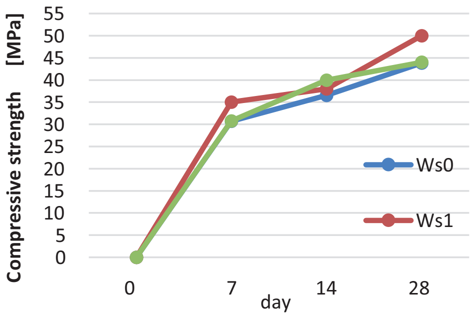

FIGURE 9. Development of compressive strength on days 0, 7, 14 and 28 for Ws0, Ws1 and Ws1.5

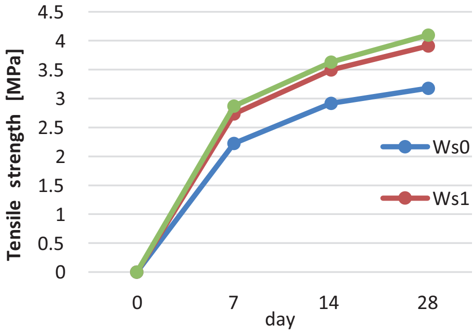

FIGURE 10. Development of tensile strength on days 0, 7, 14 and 28 for Ws0, Ws1 and Ws1.5

Conclusions

The results obtained for concrete samples containing fibres in different volumetric ratios led to the following points:

1. Addition of waste steel fibres has an effect on the compressive strength of concrete, but its effect was more pronounced on the tensile strength.
2. By increasing the percentage of fibres, the tensile strength improved up to 29% when 1.5% of steel fibres was added to concrete.
3. The addition of fibres to concrete contributed to reducing the occurrence of cracks and their widening, by creating bridges that connected the elements of the concrete. The addition of fibres also led to a change in the collapse pattern, from a brittle to a ductile failure.
4. The rate of achieving the compressive strength over time in the case of 1% of waste fibres is higher when compared with the specimens without fibres or the specimens containing 1.5% of waste fibres.
5. It was detected that the development in tensile strength was more when using 1.5% of fibres, compared to the specimens without fibres and the specimens containing 1% of fibres.

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Summary

Self-compacting concrete strengthening efficiency investigation using recycled steel waste as fibres. Steel recycling saves energy and time, and is more environmentally friendly. It can help rid the environment of huge amounts of scrap vehicles and huge structures, as well as reducing the mining operations that destroy the natural environment. In this investigation, the steel scrap effect on the mechanical properties of concrete was investigated, in addition to investigating the variation in mechanical properties with increased concrete age. Three concrete mixes were studied: one without steel waste as a control, one with 1% steel waste by volume of concrete, and one with 1.5% steel waste by volume of concrete. The results show that adding waste steel to the concrete improved the compressive strength as well as the tensile strength, where a mixture which contains 1% of steel waste had an increase in strength of up to 12% and 23% by day 28 for compressive strength, and tensile strength sequentially in comparison to the reference mix. Furthermore, the results show that there was a significant increase in splitting tensile strength, at 29% on day 28 for a mix of 1.5% steel waste as compared to the reference concrete mix. The best improvement in compressive strength over time was obtained when using 1% steel waste. The best improvement in tensile strength over time was obtained when using 1.5% of steel waste. In both cases, the amount of the improvement was better than the models without steel waste, which gives us confidence in giving recommendations for conducting more in-depth studies to achieve the maximum advantage.