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Research Article

Effect of industrial waste metal chips on flexural behavior of reinforced concrete beams

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Abstract: Recycling waste and by-products are necessary for environmentally friendly production and reducing carbon footprint. It is possible to use waste materials as additives and admixtures to improve the strength, ductility, and toughness of the reinforced concrete (RC) elements. Industrial waste metal chips have a high potential to be used as an admixture which improves the general behavior of RC elements, as proven by preliminary studies. In this study, various industrial waste metal chips were added into concrete as an admixture in different sizes and proportions to experimentally investigate the effect on the flexural strength of RC beams. Five RC beam specimens with identical dimensions and different metal chip waste admixtures were cast for the experiments. The load-displacement behavior of beams was examined by conducting a three-point bending test. As a result, it has been observed that the use of waste metal chips can significantly increase the flexural strength and ductility of the beams. The maximum load of one specimen with steel chip admixture is found to be 1.75 times higher than the waste-free reference beam. It is concluded that the usage of waste metal chips as an admixture is a viable solution to enhance the flexural behavior of the RC beams.

Keywords: Waste metal chip, reinforced concrete beam, three-point bending test, ductility, flexural strength.

1. Introduction

Using recyclable waste and by-products as input or additives in manufacturing processes is accepted as an essential method by the manufacturers. In the last decades, it has become increasingly common for the construction industry to use aggregate waste (Silva, De Brito, and Dhir 2014), brick waste (Wong et al. 2018; Wu et al. 2021), and powder (Xiao et al. 2018) from demolished structures by natural disasters or planned demolitions in ready-mix concrete production. The main reasons for this practice are energy and cost-saving and reducing environmental pollution by recycling waste. In addition, the decrease of aggregate quarry areas globally despite increasing aggregate demand is evident as another reason for this practice. According to the European Aggregates Association, aggregate production in the world ranks first in all quarrying with a share of 58%, and the aggregate production in Europe is 2.61 billion metric tons in 2020, approximately 5.9 metric tons per capita per year, but the demand is high as 3.0 billion metric tons per year (EUPG 2020).

The iron and steel industry are defined as an old and environmentally polluter. The primary metal manufacturing industry stands out as the sector that produces the most waste among the manufacturing industry. Blast furnace slag (BFS), steelwork slag, basic oxygen furnace slag (BOFS), and electric arc furnace slag (EAFS) appear as by-products in ironmaking and steelmaking. Approximately 100 kg of slag forms to produce one metric ton of steel in integrated production facilities (Topkaya, Sevinç, and Günaydın 2004). Four hundred million metric tons of iron and steel slag are produced annually worldwide (Worldsteel 2021). In proportion to the increase in metal industry and metal products processes, the amount of by-products and waste metal also increases yearly. These waste metals can be in a wide variety of shapes and properties. A limited percentage of this waste is recycled in the production processes. However, the remaining part of it is stored as waste in storehouses. The primary use areas of ironwork and steelwork slag are asphalt aggregate, filling material, substitute and additive to cement, fertilizer and soil improvement, railway ballast, road subbase, riprap material, and some other applications in the environment and agriculture (Euroslag and Eurofer 2012; Horii et al. 2015).

The oldest and most common material used in the industrial sector is iron, which is one of the most laborious industrial wastes to recycle, and comes in many shapes and forms. If this waste is not stored or recycled appropriately, it negatively affects nature and human health. This study aims to solve the problems caused by the industrial iron waste produced by the iron and steel industry by using this waste in RC elements, both to countermeasure the environmental pollution and improve the flexural strength of RC beams.

There are several studies in the literature on using various types of waste as additives and admixtures in concrete (Akhtar and Patel 2019; Batayneh, Marie, and Asi 2007; Jagan, Neelakantan, and Gokul Kannan 2021; Whittaker et al. 2021). However, studies on the industrial waste metal chip are still very scarce. The main purpose of this study is to observe the workability of concrete and to investigate the effect of various waste metal chips on the flexural strength of reinforced concrete beams. The results obtained from the experimental studies were compared, and conclusions were made regarding the results.

During industrial production, many waste materials and by-products are produced as a result of different processes. To recycle these waste materials and by-products, substituting the primary materials that compose the reinforced concrete with specific ratios is a subject that continues to be studied today. Some of these studies have tried to substitute the binding material, fine and coarse aggregate in the concrete with different materials. In some studies, waste materials are added to the reinforced concrete as additives and admixtures at varying ratios.

In the literature, one of the studies (Wang et al. 2021) focused on the effect of many different agricultural and aquacultural waste on the mechanical properties and durability of concrete. Wastes were substituted with fine/coarse aggregate and binder in the concrete in various amounts. Certain properties were improved, but some properties were reduced (workability, strength) of the concrete specimens based on waste amount. The study emphasizes that waste has excellent potential for developing environmental-friendly green concrete. Researchers (Ismail and AL-Hashmi 2008; Tian et al. 2016) also substituted specific amounts of waste iron shavings in concrete with fine material in their experimental studies. As the results of the studies, it is seen that the compressive strength of the concrete is at least as much as the concrete made with standard fine material. In addition, it was seen that the flexural strength of the RC beam produced with such materials was higher than the beam without additive. Similarly, in the studies conducted by other researchers (Alwaeli 2016; Alwaeli and Nadziakiewicz 2012), sand was substituted with waste steel chips and scale in concrete with various percentages. Moreover, some researchers also examined compressive strength and X-ray permeabilities of the produced with such materials. It has been determined that the compressive strength of the concrete with waste steel was higher than the standard concrete and had lower X-ray permeability. As such, in one of the studies, researchers (Saha and Sarker 2018) used waste steel slag in specific ratios to substitute the binder material and fine aggregate in concrete in their experimental study. As a result, it was concluded that the increase in the ratio of waste steel slag decreased the 28-day compressive strength and reduced the workability of the concrete, but the compressive strength continued to develop in later days. Waste slag is found to be a good enough replacement for binder and fine aggregate for producing green concrete. Additionally, some researchers used steel fibers as an additive to increase the tensile and compressive strength of concrete and improve the flexural behavior of RC structural elements. One of these studies (Abbass, Khan, and Mourad 2018) experimentally investigated the effect of adding hooked-ended steel fibers with different lengths and diameters on the mechanical properties of concrete for various concrete strengths. The results indicated that the addition of different content and lengths of steel fibers with increasing water-to-cement ratios caused a significant change in the mechanical properties of concrete. Also, they proposed an analytical model for the stress-strain relationship of steel fiber RC under compression. Similarly, another study (Wu, Shi, and Khayat 2019) experimentally investigated the effect of steel fibers with three different shapes and various volumes on mechanical strength, toughness, and autogenous and drying shrinkage of ultra-high performance concrete (UHCP). The most efficient steel fiber found to be hooked fibers and the use of steel fibers can enhance the compressive and flexural strengths and reduce the shrinkage of concrete. Researchers (Gülmez 2021) and (Alor et al. 2019) substituted the aggregate with waste metal in concrete production and observed higher properties with certain types of metals.

In this study, the effect of various types of waste metal chips as an admixture, which is very limited in the literature, on the flexural behavior of the RC beam was investigated with five different beams.

2. Types of waste metals

Steel is the most widely used metal both in the construction industry and in general. The fact that it is inexpensive with high tensile strength compared to other metals makes steel indispensable. Steel is an alloy that iron is the main component, mixed with low percentages of carbon. Two-thirds of steel is produced from iron ore. The remaining one-third is composed of recycled products whose main component is iron, which has completed its life cycle, or the wastes produced during the manufacture of the iron and steel industry. All the waste produced during manufacturing new steel products and objects whose main component is iron is unusable due to its age or condition, such as irreparable machinery, out-of-order vehicles, and some obsolete railway material is called metal and steel waste or scrap. The naming of some of the relevant iron and steel products in this study according to the Harmonized Classification (HC) system is shown in Table 1. HC is a classification system created to facilitate international trade for participating countries which is managed by World Customs Organization (WCO).

Table 1. Harmonized classification system for iron and steel (WCO 2022).

HC Code	Description
7201	Pig iron and spiegeleisen, in pigs, blocks, or other primary forms
7204	Ferrous waste and scrap; remelting scrap ingots of iron or steel (excluding slag, scale, and other waste from the production of iron or steel; radioactive waste and scrap; fragments of pigs, blocks, or other primary forms of pig iron or spiegeleisen)
7207	Semi-finished products of iron or non-alloy steel
7208-7212	Flat-rolled products of iron or non-alloy steel
7213-7217	Bars and rods of iron or non-alloy steel
7218-7229	Stainless steel products in various shapes and forms

Scraps are classified according to their source as revert scrap, process scrap, and prompt industrial scrap. Waste resulting from pressing, cutting, and machining are called process scraps. Therefore, waste metal chips are part of this group.

Small metal pieces that result from the process of machining or other subtractive processes are called waste metal shavings, scraps, or chips. Metal scrap is bought and sold at a lower price than other scraps. Therefore, metal scrap is one of the most recycled scraps. A schematic of a general machining process with inputs and waste outputs is shown in Figure 1.

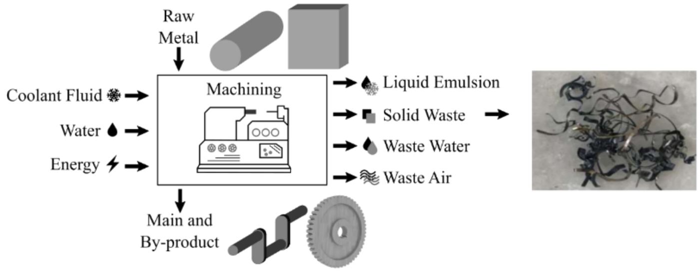


Figure 1. Material input and output flow chart in the machining process.

The European Union (EU) regulates all waste according to the European Waste Catalog (EWC) codes. EWC is a list of waste descriptions that consists of twenty main chapters. Each waste is represented with a six-digit number.

(a) (b) (c)

Figure 2. Examples of non-hazardous ferrous and non-ferrous waste Waste-1 (a), Waste-2 (b), and Waste-3 (c).

The relevant EWC codes for ferrous and non-ferrous metal wastes that are not absolutely hazardous are given in Table 2, and some ferrous metal chips and turning sample images used in this study are shown in Figure 2.

Table 2. European waste catalog code for relevant waste metals (Fortunati, Belli, and Schmitt-Tegge 1994).

EWC Code	Description
12 01 01	Ferrous metal filings and turnings
12 01 02	Ferrous metal dust and particles
12 01 03	Non-ferrous metal fillings and turnings
12 01 04	Non-ferrous metal dust and particles

3. Materials and methods

In this study, the effect of industrial waste metal chips in various shapes and sizes as an admixture on the flexural behavior of RC beams was investigated. Both workability of the concrete and the flexural strength of the RC beams were compared among the different types of waste metal chips tested. Three different waste metal chips varying in size and shape were selected as admixtures, one of which has two different waste materials in combination. Apart from the four RC beams cast with waste admixtures, a reference beam without waste was produced for comparison.

The test specimens are numbered from K0 to K4, with K0 serving as the reference beam. To ascertain the compressive strength of concrete, a total of nine standard cube samples, each measuring 150 mm, were prepared for every specimen.

Reinforcement details for all specimens were selected as 2Ø12 rebar as compression and 2Ø12 rebar as tension with one Ø8 stirrup at each end.

3.1. *Cement and aggregate*

A standard pozzolanic cement with a strength class of 32.5 with an ordinary early strength was used for concrete which conforms to TS EN 197-1 standard. The cement was in group CEM IV according to standard, and the laboratory results of the chemical composition of the cement were given in Table 3. Loss of ignition (LOI) of the cement was measured as 4%, specific gravity and surface area of the cement used in the mixtures were 2.87 and 4450 cm2/gr respectively.

Table 3. Chemical composition of cement used in test specimens.

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_2	Na_2O	K_2O	Cl^-
Percent Composition by Mass (%)	28.46	7.88	3.19	47.96	1.82	2.05	1.23	1.71	0.0271

A mixture of three different aggregate sources with different maximum diameters (1mm-5mm, 5mm-12mm, 12mm-22mm) was used to prepare a standard (TSI 2019) conforming distribution of fine and coarse aggregates. Sieve analysis according to ASTM C136M-19 (ASTM 2020a) with ASTM 11-20 (ASTM 2020b) compliant sieve set of the aggregate used in the concrete was given in Table 4.

Table 4. Sieve analysis of aggregate used in test specimens.

Sieve Size	Percent Retained (%)	Cumulative Percent Retained (%)	Percent Passing (%)	Recommended Percent Passing as per EN12620 (TSI 2019) (%)
37.50 mm	0.0	0.0	100	--
25.00 mm	0.0	0.0	100	100
19.00 mm	12.7	12.7	87.3	89-96
12.50 mm	13.1	25.8	76.2	73-86
9.50 mm	20.5	46.3	55.7	54-71
4.75 mm	15.8	62.1	39.0	37-56
2.00 mm	12.3	74.4	28.5	25-43
425 microns	5.6	80.0	12.9	6-15
180 microns	8.7	88.7	9.7	3-10
75 microns	6.5	95.2	4.9	1-5
Pan	4.8	100.0	0.0	0

The specific gravity of the fine and coarse aggregates used in the mixtures were measured as 2.584 gr/cm^3 and 2.714 gr/cm^3, respectively.

3.2. *Waste metal*

Three waste metal chips of various sizes and shapes used in this study were obtained from two different industrial regions and three different metal manufacturers in Turkey. A mixture of AA 6013 aluminum waste and AISI 1008 steel waste is named Waste-1 (Figure 2a), a mixture of AISI 4140 steel waste and AISI 8620 steel waste is named Waste-2 (Figure 2b), and a mixture of AISI 1050 steel waste and AISI 1040 steel waste named as Waste-3 (Figure 2c). Those mixtures of metals were selected since they were readily available locally in bulk as waste from metal manufacturers. For a more accurate comparison of the specimens, the waste metal chips were shredded to even lengths. Before these industrial waste metal chips are added to the concrete, their unit weights and specific weight are measured as γs=7.69 gr/cm^3 (γs=75.44 kN/m^3) for steel and γa=2.65 gr/cm^3 (γa=26.00 kN/m^3) for aluminum.

Waste metal chips were cut in same lengths for all the specimens with tin snip. The detail of the lengths given in respective topics below.

3.3. *Test specimens*

The specimens were tested with a three-point bending test that has a single concentrated load at midspan. A total of five RC beams were cast on the same day, as one reference beam that was admixture-free and four RC beams that had waste metal chips in various types and shapes as admixtures (Aslan 2020). In Table 5 material distribution of the test specimens were given.

The cross-section of all test specimens is 250 mm x 250 mm, and the length is 1000 mm, as shown in Figure 3. A stirrup with an 8 mm diameter was placed at each end of the test specimens to hold the rebars in position while the casting process. The ratio of the shear span of the beams to the effective height (a/d) is calculated as 1.78. The waste metal chip weights used in specimens and specimen properties are given in Table 6.

Table 5. Material distribution of test specimens by weight.

Specimen Name	Specimen Weight (W_c=V_c·γ_c) (kg)	Weight in 1m^3 (kg)				Weight Percentage (%)			
		Water	Cement	Aggregate	WMC*	Water	Cement	Aggregate	WMC*
K0	138.8	224.6	249.6	1746.5	-	10.1%	11.2%	78.6%	-
K1	143.0	224.6	249.6	1746.5	68	9.8%	10.9%	76.3%	3.0%
K2	143.0	224.6	249.6	1746.5	68	9.8%	10.9%	76.3%	3.0%
K3	146.0	224.6	249.6	1746.5	116	9.6%	10.7%	74.7%	5.0%
K4	143.0	224.6	249.6	1746.5	68	9.8%	10.9%	76.3%	3.0%

*: Waste metal chip

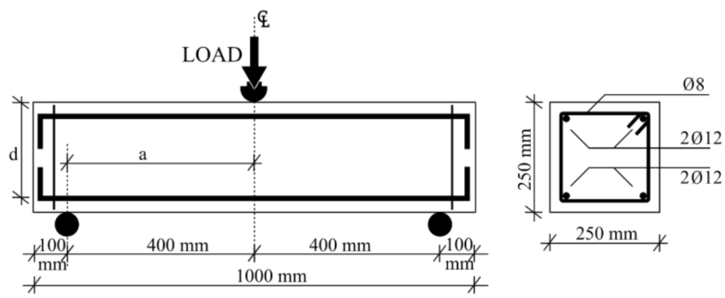


Figure 3. Test setup and cross-section of specimens.

Table 6. Dimensions and properties of specimens and waste types.

Test Specimen Name	Waste Amount by Weight Percentage and Type	a/d ratio	Length (mm)	Compression Rebar (mm^2)	Tension Rebar (mm^2)
K0	-	1.78	1000	2Ø12 (226)	2Ø12 (226)
K1	3.0% of Waste-1				
K2	3.0% of Waste-2				
K3	5.0% of Waste-3				
K4	1.5% of Waste-2 + 1.5% of Waste-3				

For RC beam specimens, concrete compressive strength was intentionally selected as 8 MPa to understand better the effect of waste metal chips on the beam flexural strength. The average compressive strengths of the concrete without waste metal chips on the 7th, 28th, and on the test day (45th day) are experimentally found according to TS EN-206+A2 (TSI 2021) given in Figure 4. The average concrete compressive strength was found as 8.9±0.3 MPa on the test day (45th day). The mechanical properties of the waste metal chips are comparatively unpredictable and not consistent between different batches due to various production technics and exposure to high heat during the machining process.

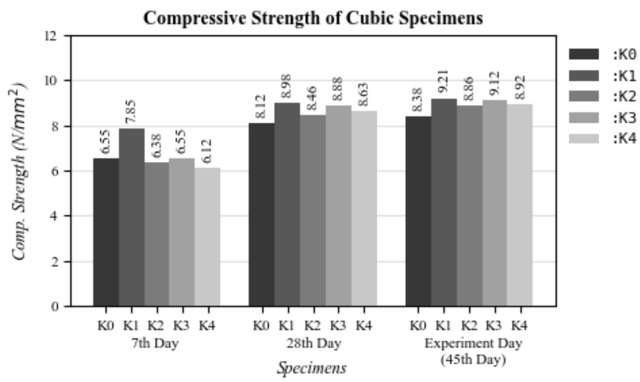


Figure 4. Compressive strength of standard cubic concrete specimens for 7th day, 28th day, and experiment day (45th).

3.4. *Test setup*

The loading frame and the experimental setup are shown in Figure 3, and a picture of the setup with the K0 specimen can be seen in Figure 5. The loading speed was selected as a constant 0.5 mm per minute throughout the test. The displacement at the midspan and applied force were measured with an LVDT and a load cell, respectively.

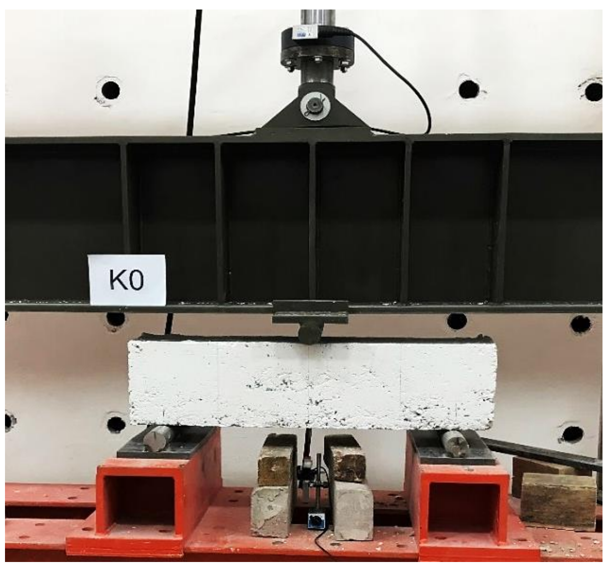


Figure 5. Loading frame with K0 specimen

4. Experiment results

All test specimens were subjected to a three-point bending test, as seen in Figure 5. The crack formations and deformations of all beams at the end of the tests are given in Figure 6. The load-displacement curves of all beam specimens are given in Figure 7.

Table 7. Force and displacement values at extremum points.

Specimens	f_{cr} (kN)	f_u (kN)	$0.85f_u$ (kN)	Δ_u (mm)	Δ_f (mm)	Δ_{max} (mm)
K0	27.50	83.60	70.81	4.7	7.1	52.5
K1	37.27	92.54	78.66	6.1	15.1	42.1
K2	47.07	125.45	106.60	5.6	8.2	28.2
K3	47.57	93.03	79.07	4.5	6.9	30.6
K4	34.32	146.10	124.06	6.5	8.7	24.7

Table 7 shows the extremum values for force and midspan displacement that are given on the graph in Figure 7. In the table, f_{cr} represents the first noticeable crack load, f_u represents the maximum load that specimen has ever reached, and Δ_u represents the midspan displacement at that point. $0.85f_u$ represents the failure load where the load dropped 15% from the f_u, and Δ_f is the midspan displacement at the failure load. Also, Δ_{max} shows the midspan displacement when the test ended.

4.1. *Beam specimen K0*

During the experiments, the first noticeable crack in the K0 beam occurred at a load of 27.5 kN, where the midspan displacement is 0.8 mm. The number, length, and width of cracks were observed as the load, and midspan displacement increased. In addition, it has been noted that the crack formations occurred from the supports towards the load application point. Midspan displacement measured 4.7 mm under a maximum load of 83.60 kN for the K0 reference specimen.

4.2. *Beam specimen K1*

The K1 beam specimen contains two different wastes, aluminum and steel chips called Waste-1. Waste 1, containing aluminum in the form of fine wire in different widths and spiral iron shavings in different lengths, was obtained from local companies.

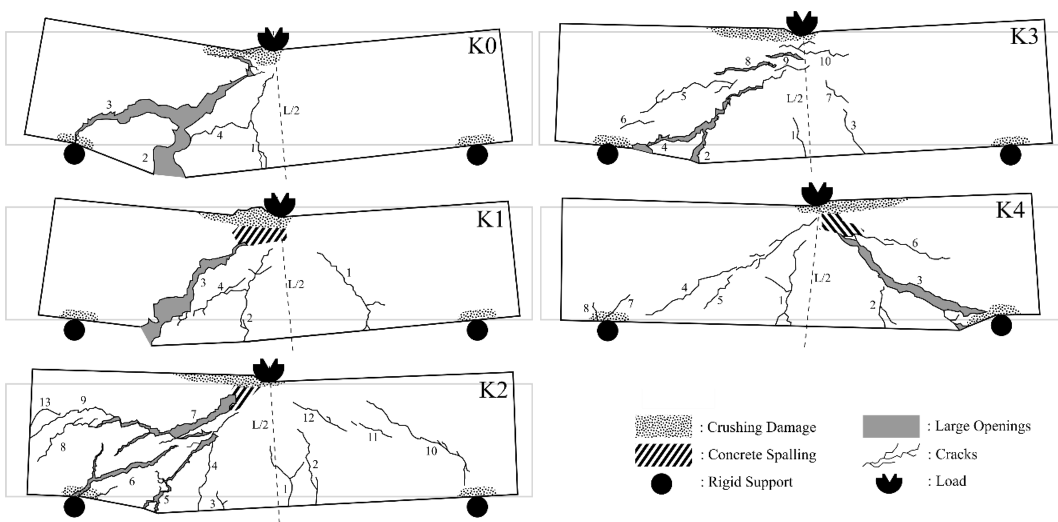


Figure 6. Crack formation of beam specimens after failure.

The waste metal chips were cut approximately 100 mm in length using tin snips to ensure the uniform distribution of the shavings in the concrete. However, the waste chips intertwine with each other, which negatively affects uniformity before and after cutting. The width of the aluminum chips in Waste 1 is between 2 mm and 3 mm, while the width of the steel chips is between 0.5 mm and 1 mm. Also, the thickness of the chips is about 0.8 mm for both.

After the three-point bending test, the crack pattern of the K1 beam, cast with Waste-1 as admixture, is shown in Figure 6. The first noticeable crack in the K1 beam occurred at 37.27 kN load level, where the midspan displacement was 1.5 mm during the experiment, which is a higher value than the reference specimen. The midspan displacement of 6.1 mm is measured under the maximum load of 92.54 kN for this beam specimen.

Due to the long and spiral shape of the waste metal chips in the K1 beam, waste chips act as a shear reinforcement between the cracks, slow down the spread of existing cracks, and decrease the formation rate for new cracks. In addition, since iron waste has a thin but spiral structure, it strongly bonds with concrete and prevents crack formation up to a certain point.

4.3. *Beam specimen K2*

The K2 beam was cast using wide and brittle steel waste called Waste-2 as an admixture. Waste 2, which has the widest and longest shavings, also consists of shavings that split more easily, even with a hand, than other types of waste. The shavings in Waste-2 were split and cut to approximately 100 mm in length to get mixed more uniformly in the concrete. The width of the shavings varies between 5 mm and 10 mm, and the thickness is approximately 0.8 mm for each waste.

The formation of the cracks in the K2 beam as a result of the test is shown in Figure 6. The first noticeable crack in the K2 beam occurred at 47.07 kN load level, where the midspan displacement was 1.9 mm during the experiment. Cracks formed symmetrically along the beam, and the angle of the cracks became vertical to 45 degrees going from midspan to near supports as in the K0 and K1 beams. The midspan displacement of 5.6 mm is measured under the maximum load of 125.45 kN for this beam specimen.

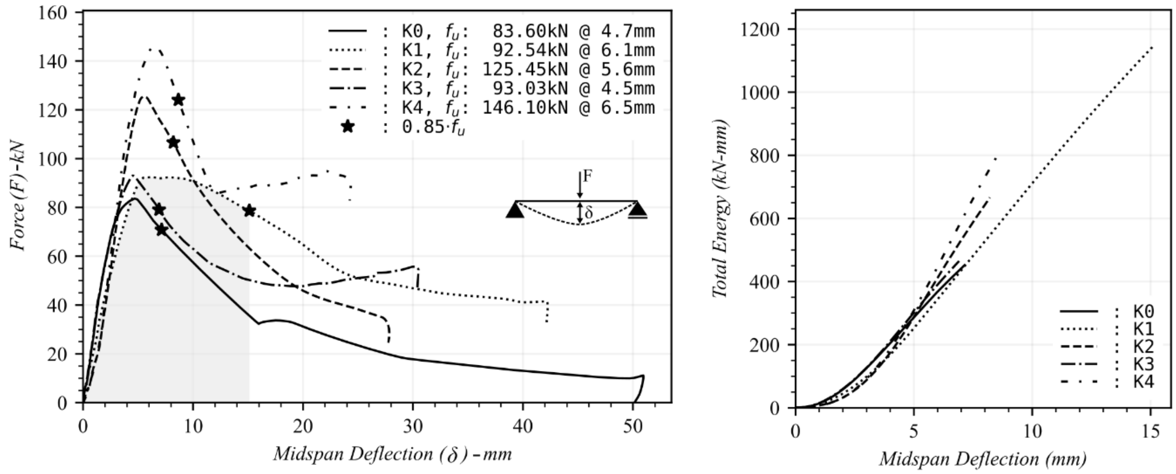
4.4. *Beam specimen K3*

K3 beam specimen was cast with Waste-3 admixture. Waste-3 consists of small shavings, also called dust shavings, that come out of and accumulate under the lathe. Therefore, no additional processing was required regarding its length. Waste-3 was more uniformly distributed within the K3 beam specimen than other waste. The lengths of the shavings vary between 5 mm and 60 mm, and widths vary between 0.5 mm and 10 mm (Figure 2c).

The first noticeable crack formed in the K3 beam during the experiment has almost the same load level as the K2 beam specimen and occurred during the loading level of 47.57 kN with a midspan displacement of 1.3 mm. The cracks formed are similar to the K1 and K2 beam specimens. The midspan displacement of 4.5 mm is measured under the maximum load of 93.03 kN for this beam specimen.

4.5. *Beam specimen K4*

Unlike other beam specimens, the K4 beam specimen was cast with two different admixtures of equal weight that is Waste-2 and Waste-3. The first noticeable crack in the K4 beam occurred at 34.32 kN load level, where the midspan displacement was 1.7 mm during the experiment. The cracks on the K4 beam formed symmetrically and progressed from the supports to the load application point, as in the other test elements. The midspan displacement of 6.5 mm is measured under the maximum load of 146.10 kN for this beam specimen. K4 beam specimen reached the highest maximum load among the beam specimens, including the K0 reference beam with no admixture.



(a) (b)

Figure 7. Load-midspan deflection (a) and the total energy (b) of the beam specimen.

5. Discussion

In this study, one standard reference RC beam and four RC beams with waste metal chip admixtures were examined under a three-point bending test. Crack formations and load–midspan displacements were presented, and the flexural strength of the beams was investigated. When the midspan displacement and load curves (Figure 7) were examined, it was seen that the waste-free reference beam specimen K0 has a lower maximum load and ductility than the other specimens with waste metal admixture. In other words, it can be said that the waste chips increase the flexural strength of all beam specimens to a certain extent.

During the bending test, the increase in the first noticeable crack load of the specimens with waste admixture is higher between 1.25 and 1.73 times than the K0 reference beam specimen (Table 7). In the first noticeable crack formation, the highest displacement has occurred in the K2 and K3 specimens, while the K1 and K4 specimens have the highest initial crack load. Before the failure, the K1 beam specimen reached the highest displacement value.

At the beginning of evaluating the test results to determine the properties of the materials, the determination of the maximum strength comes first. Strength is one of the most defining features of material behavior. Therefore, one of the primary purposes of this experimental study is to determine the maximum strengths of the test specimens. In the experiments, the K4 beam reached the highest maximum load value of 146.10 kN. This is because the K4 beam has Waste-2 with a spiral shape that has high adherence with concrete and Waste-3 with the widest shavings than the other waste is used as an admixture in equal proportion.

The difference between maximum loads between specimens that changes from 92 kN to 146 kN shows that the mechanical properties of the chips are an effective parameter of flexural strength. The least maximum load increase was observed in the K1 beam specimen compared to the waste-free reference test specimen. To better determine the effect of waste chips under the bending test, the use of beams without shear reinforcement and short span has been a very significant factor.

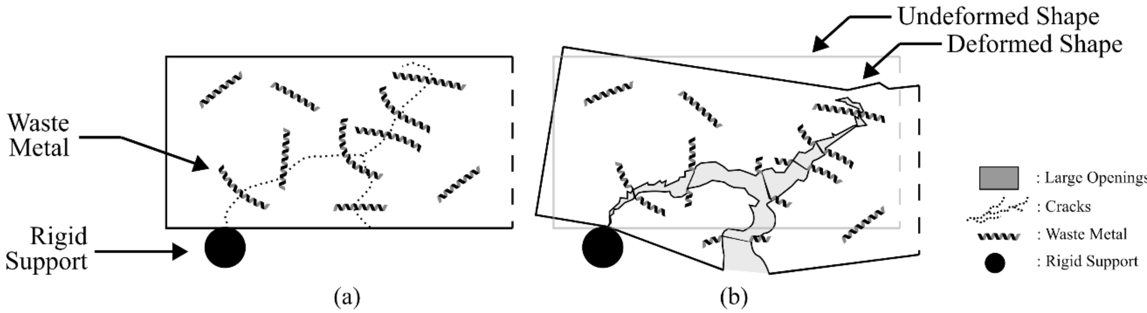


Figure 8. The waste metal chips in the RC beam before loading (a) and after loading (b).

Another essential feature in determining an engineering material's strength is ductility, which defines the ability to deform under load. Ductility is an effective parameter in the comparison of materials. If we consider ductility as the displacement ratio at the failure to the maximum load, in this study, the most ductile test specimen (15.07/6.1=2.47) is the K1 beam. It can be said that the reason for this is the link-like behavior of the waste chips used in this test specimen, which is similar behavior to the steel fibers mentioned in the introduction. The order of ductility of the test specimens is K1, K3, K0, K2, and K4 from highest to lowest. In this study, no stirrups were used to counter the shear forces so that the effects of the waste chips on the beam flexural strength can be seen as more prominent. It could be said that the ductility of the beam specimens would be higher if stirrups were used because it is known that shear reinforcements increase ductility.

In addition, the failure load and displacement are effective parameters in the structural design and computation of structural behavior because this failure point is used in the deformation-based approach to structural design. As in maximum load, the K4 beam specimen has a maximum failure load of 124.06kN. Displacements in the case of failure differ between specimens.

It is seen that the mechanical properties of the waste chips used in the test specimens are effective in flexural strength. When the test results of the K1 beam manufactured with Waste 1 were compared with the test specimens manufactured with others, it was observed that as the waste chip width increases, the displacement decrease while the ductility of the beam increases. It is seen that the flexural strength and ductility of the K3 beam are lower since this test specimen has the lowest workability, and the concrete could not get completely in the spiral waste chips and thus decreasing the bonding between the waste chip and concrete. Similarly, Waste-1 decreased the maximum load of the K1 beam but increased the ductility since it did not mix with the concrete thoroughly.

Figure 8a schematically shows the distribution of metal chips in the beam specimen, and Figure 8b shows the behavior of the metal chips as the beams crack during the test. By examining this figure, it can be seen that the metal chips act as a link element during the crack formation and do not allow the concrete parts separated from the main body of the beam to break off and fall. Although it is not the scope of this study, it can be said that this behavior could improve the bending behavior of the beams under reversed cyclic loads. In addition, this linkage behavior counters some of the shear forces occurring close to supports. This can be understandable from the failure types of the beam specimens when compared between waste-free reference beam K0 and other beam specimens with waste metal admixtures. This behavior is very similar to hooked-ended steel fiber researches (Abbass et al. 2018; Wu et al. 2019).

Figure 7b shows the change of total area under the force and midspan displacement curve until the failure load. This graph can be read as the total energy spent till the beam failure. K1 beam specimen has the highest total area as expected, which also has the most ductile specimen. The waste metal admixtures increased the total energy absorption capacity more than two-fold for the K1 specimen and significantly for other specimens compared to the K0 reference beam.

The shear forces formed by a vertical load in the beams create shear cracks (45-60 degrees depending on the beam height) in the regions close to the supports where the shear force is higher (Figure 6). In general, to prevent these cracks from forming, stirrups need to be arranged perpendicular to these shear cracks formed on the beams. While the stirrups are placed at frequent intervals in sections for high shear forces, fewer stirrups will be adequate in sections with lower shear forces. The failure of structural elements resulting from shear cracks is an unwanted failure type because it is brittle behavior and happens in a short time with no notice beforehand. Therefore, all modern structural design codes have the necessary criteria to prevent shear failures and minimum requirements to compensate for shear. Due to the lack of reinforcements to counter the shear force in the beam specimens tested in this study, it was observed that the failure of the beams was due to shear cracks.

The authors of this paper want to draw attention to the corrosion problem by using metallic waste as an admixture in the concrete. As known, all the design codes force an obligatory minimum concrete cover to protect structural steel from corrosion. However, it is not possible to prevent corrosion on waste metals exposed on the concrete surface without taking additional measures while using metallic waste. Although this aspect of recycling is out of the scope of this study, more research should be done before this method become a common practice.

6. Conclusion

It was observed that the waste metal chips used in this series of experiments increased the ductility of the beams, flexural strength, and energy absorption capacity. The increase in ductility, which is as effective as strength, shows that waste metal chips could be beneficial in designing structural elements. In addition, the fact that the area under the load-displacement curve for the specimens with waste chip admixture is larger compared to the reference specimen shows that the chips increase the toughness of the beams. By examining the cracks formed throughout the loading, it was observed that the split chunks did not separate from the main body of the beam since the waste metal chips acted as fibers in the cracks. In addition, the waste metal chips served as link elements (Figure 8) that counter the shear forces.

Thus, waste metal chips countered part of the shear forces along with the concrete, although the shear strength of the concrete is deficient due to the low compressive strength of the concrete. This behavior can be seen from load-displacement graphs (Figure 7) as a delayed failure compared to the reference beam K0, which admittedly failed after shortly the maximum load was reached. In other words, all other specimens failed at higher displacements compared to K0. This behavior is an important aspect that increases the ductility of the beams. The production cost of waste metal, which is inevitable during manufacturing, is too low to consider. Moreover, the benefits provided by this waste metal admixture in this experimental study show that RC beam production is a viable process to reuse for this type of waste.

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