Construction and Building Materials 221 (2019) 109–121

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of recycled nano carbon black and waste erosion wires in electrically conductive concretes

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HIGHLIGHTS

- Electrically conductive concrete (ECON) was produced with 36 different mixtures proportions.
- Four different materials were used as electrically conductive additive in concrete mixtures.
- Recycled nano carbon black (RNCB) and waste wire erosion (WWE) were evaluated in ECON.
- RNCB increased the conductivity effect of CF by 2–7 times.
- In mixtures containing WWE, lower resistances as 129 Ω.cm were obtained.

ARTICLE INFO

Article history:
Received 18 March 2019
Received in revised form 13 May 2019
Accepted 3 June 2019

Keywords:
Electrical conductive concretes
Carbon fiber
Nano carbon black
Wire erosion
Steel fiber

ABSTRACT

Increasing number of studies have focused on the materials to impart electrical conductivity into concretes. Yet, economical concerns hinder the use of conductive materials in large-scales. This study investigates the performance of electrical conductive additives obtained from waste materials on the mechanical and conductive behavior of concretes. 36 different concrete mixtures containing carbon fiber (CF), recycled nano carbon black (RNCB), waste wire erosion (WWE) and steel fiber (SF) were prepared. Carboxymethyl cellulose was used as the fiber distributor. Mechanical behavior of specimens were characterized through compressive and flexural tests along with impact experiments. Bulk and surface resistance measurements were performed for electrical conductivity analysis of concrete specimens. SEM analysis were carried out to display the amount and morphology of porosities inside concrete. Our results indicate that RNCB has significant effect on the reduction of electrical resistance when used in combination with other fillers. Besides, WWE were shown to be effective in the reduction of resistivity both in the use of alone and combined with small amount of CF. Our cost analysis reveals that electrical conductive concretes (ECON) prices can be diminished up to 40% through utilizing waste materials without the sacrifice of mechanical properties.

1. Introduction

Since the discovery of electrical conductive concretes (ECON), i.e. from 1965 [1], various investigations have been carried out on the conductivity of cement mortars and concretes. ECONs are utilized in self-sensing material of buildings as electromagnetic radiation reflector for electromagnetic interference shielding and resistance material in self-heating floor systems (SHFS) [2–5]. Recently, SHFSs have been applied in roads and airport runways to prevent the accumulation of ice and snow through melting by the self-heat emitted from concrete [6–10].

High electrical resistance of concretes were confirmed by different authors. Electrical resistivity of open air dried concrete was measured as 6.54×10^5–$11 \times 4\ 10^5$ Ω-cm [5–11]. In addition, electrical resistance of saturated and dry concrete were reported as 10^6 Ω-cm and 10^9 Ω-cm, respectively [12,13]. Considering a single matrix, concrete locates between conductive and semi-conductive materials in electrical conduction. Conductivity of concrete can be increased with the addition of various conductive additives [14–20]. The amount of conductive additives should be precisely adjusted in order to prevent the deterioration of other mechanical and physical properties of the concrete. Powder materials such as graphite, carbon black and one-dimensional conductive materials

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https://doi.org/10.1016/j.conbuildmat.2019.06.025
0950-0618/

such as, steel fiber (SF) and carbon fiber (CF), have been utilized in different studies [6,18,21–37]. Steel fiber is one of the most commonly used materials for improving the properties of concrete, such as tensile, flexural, shear and toughness. Steel fiber was also used as a conductive additive material since the first ages of the production of conductive concrete [6,16,38]. Among those fillers, CF utilized in the production of electrically conductive cementitious composites which were also shown to having better physical and mechanical properties [5].

El-Dieb [12] examined the behavior of different conductive fillers in multi-functional electrical conductive concretes. The concrete mixture was designated to have a compressive strength of 30 MPa. As a conductive filler material, four different weight percentage (1%, 3%, 5% and 7 wt%) of steel shavings, carbon and graphite powder were used. According to the results, electrical resistance (ER) and compressive strength were decreased with the increase of all three fillers where the most severe reduction of compressive strength was observed in steel shavings. Besides, graphite was also found to be most effective in the reduction of resistance.

In conductive cementitious materials and concretes, other materials such as steel wool, carbon nano fibers and tubes have been investigated [36,37,39–41]. In order to increase the conductivity of concrete, conductive additives can be used as either single or multi-phases. Wu et al. [6] examined the properties of three-phase electrical conductive concretes produced in order to prevent freezing in road superstructures. In conductive mixtures, graphite, SF and CF were used as conductive additives. According to the results, the compressive strength and ER value decreased with increasing the graphite ratio in the composite concretes containing SF and graphite. In three-phase composite concretes, it was determined that the maximum compressive strength yields in the composite containing 1.2 wt% SF, 0.4 vol% CF and 6 wt% graphite and the minimum ER value belongs to composite containing 1.0 vol% SF, 0.4 vol% CF and 4 wt% graphite.

According to the results obtained from different researches, the size and distribution of the filler material were found to be more important than the conductivity and amount of the material used in order to affect the concrete conductivity [12,25]. Some researches were shown the importance of component type, aggregate content, water-cement and sand-cement ratio in the electrical resistance of concretes [26,42–46].

Sassani et al. [5] investigated the effect of five different variables on the engineering properties of electrically conductive concretes. Variables; CF dosage, fiber length, coarse-fine aggregate volume ratio (C/F), conductivity increasing agent (CIA) dosage and fiber dispenser agent (FDA) dosage. Decrease in electrical resistance was observed with increasing CF amount, and the length of fiber was determined to be insignificant in decreasing resistance. The resistance increased with increasing C/F ratio. Increase in the amount of CIA significantly reduced the resistance. The presence of FDA decreased resistance independent of its amount. In CF containing concretes, methyl cellulose agent is generally used as dispersant [5,47,48].

This study aims to utilize two different waste materials to reduce the cost of electrical conductive concretes. Recycled Nano Carbon Black (RNCB) obtained from waste tires by pyrolysis method was used as powder additives. In addition, cropped waste erosion wire and carbon fiber were used as the fiber.

2. Materials and methods

2.1. Material properties

2.1.1. Cement and aggregate

In this study, 42.5 CEM I R type high strength cement was preferred as binder material. EDS analysis of the cement used are summarized in Table 1. Coarse aggregate (CA) and fine aggregates (FA) were used as filler material. Table 2 shows the grading of used aggregates.

2.1.2. Steel fiber

In the mixtures, a steel fiber type with of 30 mm in length, 0.75 mm in diameter, and 1400 MPa in tensile strength was used. Weight ratio of steel fiber in all mixtures was selected as 2 wt% (48 kg/m^3).

2.1.3. Waste wire erosion (WWE)

WWE is a conductive wire used in electrical discharge machining (EDM) for cutting work pieces. By passing electrical current through the wire erosion, the workpiece is abraded and cutting takes place. Roughness occurs on the wire erosion surface [49] after processing the metal piece which is an advantage for adherence between WWE and cement paste. In this study, yellow colored CuZn37 alloy waste wire erosion with 0.25 mm in diameter and average 25 mm in length was used. Electrical resistance of wire erosion was measured as 0.00256 Ω-cm.

2.1.4. Carbon fiber (CF)

In this study the effect of CF on the electrical properties of concrete were investigated utilizing three different amount of CF in the mixture. Carbon fiber used has a filament diameter of 7.2 µm and a length of 6 mm and 12 mm in equal proportions. In previous studies, CF containing batches were shown to having better resis-

Table 2
Gradation tables of coarse and fine aggregates.

Coarse aggregate		Fine aggregate	
sieve size (mm)	cumulative retained (%)	sieve size (mm)	cumulative retained (%)
20	0	4.75	0
16	17	2.36	18
12.5	62	0.60	43
10	78	0.30	79
4.75	100	0.15	91
		<0.15	100

Table 1
EDS analysis results of cement.

Element	Line	Intensity (c/s)	Error 2-sig	Conclusion	Units	
C	Ka	0.06	0.156	0.048	wt.%	
O	Ka	14.29	2.390	25.508	wt.%	
Al	Ka	7.75	1.760	1.192	wt.%	
Si	Ka	89.23	5.972	11.860	wt.%	
K	Ka	2.66	1.030	0.321	wt.%	
Ca	Ka	407.91	12.768	59.666	wt.%	
Fe	Ka	4.65	1.363	1.405	wt.%	
				100.000	wt.%	Total

Table 3
Properties of used CF.

Tensile Strength	3800 MPa
Modulus of Elasticity	228 GPa
Electrical resistance	0,00155 ohm-cm
Specific weight	1,81 gr/cc
Carbon Percentage	%95

tance to freezing-thawing, tensile strength, fatigue, shrinkage potential and expansion sensitivity [47,50,51]. The properties of CF used in this study are given in Table 3.

2.1.5. Recycled nano carbon black (RNCB)

Carbon is one of the many elements known since ancient times. It is also the fourth most common chemical element in the universe. RCNB has been commercially produced for nearly hundred years. This study aims to make use of nano carbon black, obtained by pyrolysis method from waste tires, in conductive concrete mixtures. Specific surface area of nano carbon black obtained by pyrolysis method were shown to increased up to 80–90 m^2/g by elevating the applied temperature to 600 °C during the production [52]. RNCB obtained by pyrolysis method located between N200-N330 according to ASTM nomenclature [53].

2.1.6. Chemical additives

Fine CF and RNCB containing concrete mixtures require excessive water due to the high specific surface area of these materials. A superplasticizer (SP) with a commercial name of CHRYSO® Delta 2220 was used to reduce the need for water. Methyl cellulose was used in most studies to ensure the good distribution of CF in the concrete mixture. In this study, carboxymethyl cellulose (CMC) was used as fiber dispersing agent. The CMC was dissolved in water in 0.2 wt% of the binder and added to the concrete mixture.

2.2. Mix design

Literature analysis reveals that the optimum amount carbon fiber used in electrically conductive concretes are 0.75–1 vol% [5,54]. Since the combined use of CF along with RNCB, we adjusted. However, no study has been reported on the combined use of CF and nano carbon black, in this study it was aimed to obtain the optimum CF and RNCB amount by using three different ratios of CF and RNCB in concrete mixtures. In SF-containing mixtures, SF was used as 2 wt% (48 kg/m^3).

In all mixtures C-aggregate: F-aggregate: cement ratio was taken as 1: 1: 0.5. In the mixtures, the water/binder ratio was kept at 0.45 and the variable superplasticizer additive was used to improve the workability. For the workability and consistency of the concrete containing CF, slump test is not a suitable indicator as the mixture may exhibit low slumps while having sufficient workability and consistency [54]. In this study, the slump of the control concrete mixture was set to approximately 80 mm, and with the addition of CF this value was decreased to about 40 mm. In the mixture, as the CF ratio increased, the cement paste ratio decreased, but with the increase of RNCB in the same mixtures, this challenge was eliminated. As a result, no problems were encountered regarding the workability, molding and compacting of all mixtures summarized in Table 4.

In the first phase of the study, after the results of the specimens containing CF and RNCB were determined, specimens of the same size were produced by designing four different mixtures contain-

Table 4
Materials used in 1 m^3 mixture – first stage.

No	Mixture code	FA (kg)	CA (kg)	Cement (kg)	W(kg)	SF (kg)	WWE (kg)	RNCB (kg)	CF (kg)	CMC (Wt. %)	SP (Wt. %)	Cost ($)
1	Control	850.00	850.00	425.00	191.25	0.00	0.00	0.00	0.00	0.00	0.50	50.95
2	N3C0S0*	844.90	844.90	422.45	195.84	0.00	0.00	12.75	0.00	0.00	0.50	68.16
3	N6C0S0	839.80	839.80	419.90	200.43	0.00	0.00	25.5	0.00	0.00	0.50	85.38
4	N10C0S0	833.00	833.00	416.50	206.55	0.00	0.00	42.50	0.00	0.00	0.75	108.33
5	N0C0.2S0	848.53	848.53	424.26	190.92	0.00	0.00	0.00	3.60	0.20	0.75	223.75
6	N3C0.2S0	843.43	843.43	421.72	195.51	0.00	0.00	12.75	3.60	0.20	0.75	240.96
7	N6C0.2S0	838.33	838.33	419.17	200.10	0.00	0.00	25.5	3.60	0.20	0.75	258.18
8	N10C0.2S0	831.56	831.56	415.78	206.23	0.00	0.00	42.50	3.60	0.00	1.00	281.13
9	N0C0.5S0	846.43	846.43	423.22	190.45	0.00	0.00	0.00	9.00	0.20	1.25	482.95
10	N3C0.5S0	841.33	841.33	420.67	195.04	0.00	0.00	12.75	9.00	0.20	1.25	500.16
11	N6C0.5S0	836.23	836.23	418.12	199.63	0.00	0.00	25.5	9.00	0.00	1.50	517.38
12	N10C0.5S0	829.43	829.43	414.72	205.75	0.00	0.00	42.50	9.00	0.20	1.50	540.33
13	N0C1S0	842.78	842.78	421.39	189.63	0.00	0.00	0.00	18.00	0.00	1.75	914.95
14	N3C1S0	837.68	837.68	418.84	194.22	0.00	0.00	12.75	18.00	0.00	1.75	932.16
15	N6C1S0	832.58	832.58	416.29	198.81	0.00	0.00	25.5	18.00	0.00	1.75	949.38
16	N10C1S0	825.78	825.78	412.89	204.93	0.00	0.00	42.50	18.00	0.00	2.00	972.33
17	N0C0S2	830.80	830.80	415.40	186.93	48.0	0.00	0.00	0.00	0.00	0.50	108.55
18	N3C0S2	825.70	825.70	412.85	191.52	48.0	0.00	12.75	0.00	0.00	0.50	125.76
19	N6C0S2	820.60	820.60	410.30	196.11	48.0	0.00	25.5	0.00	0.00	0.50	142.98
20	N10C0S2	813.80	813.80	406.90	202.23	48.0	0.00	42.50	0.00	0.00	0.75	165.93
21	N0C0.2S2	829.36	829.36	414.68	186.61	48.0	0.00	0.00	3.60	0.00	0.75	281.35
22	N3C0.2S2	824.26	824.26	412.13	191.20	48.0	0.00	12.75	3.60	0.00	0.75	298.56
23	N6C0.2S2	819.16	819.16	409.58	195.79	48.0	0.00	25.5	3.60	0.00	0.75	315.78
24	N10C0.2S2	812.36	812.36	406.18	201.91	48.0	0.00	42.50	3.60	0.00	1.00	338.73
25	N0C0.5S2	827.20	827.20	413.60	186.12	48.0	0.00	0.00	9.00	0.00	1.25	540.55
26	N3C0.5S2	822.10	822.10	411.05	190.71	48.0	0.00	12.75	9.00	0.00	1.25	557.76
27	N6C0.5S2	817.00	817.00	408.50	195.30	48.0	0.00	25.5	9.00	0.00	1.50	574.98
28	N10C0.5S2	810.20	810.20	405.10	201.42	48.0	0.00	42.50	9.00	0.00	1.50	597.93
29	N0C1S2	823.60	823.60	411.80	185.31	48.0	0.00	0.00	18.00	0.00	1.75	972.55
30	N3C1S2	818.50	818.50	409.25	189.90	48.0	0.00	12.75	18.00	0.00	1.75	989.76
31	N6C1S2	813.40	813.40	406.70	194.49	48.0	0.00	25.5	18.00	0.00	1.75	1006.98
32	N10C1S2	806.60	806.60	403.30	200.61	48.0	0.00	42.50	18.00	0.00	2.00	1029.93
33	N6C0W0.5*	822.80	822.80	411.40	196.61	0.00	42.50	25.5	0.00	0.20	0.75	191.63
34	N6C0W1.0	805.80	805.80	402.90	192.78	0.00	85.00	25.5	0.00	0.20	0.75	297.88
35	N6C0.2W1.0	804.36	804.36	402.18	192.46	0.00	85.00	25.5	3.60	0.20	1.6	470.68
36	N6C0.2W1.5	787.36	787.36	393.68	188.63	0.00	127.5	25.5	3.60	0.20	1.6	576.93

*N: Recycled Nano Carbon Black, C: Carbon Fiber, S: Steel Fiber, E: Waste Wire Erosion.

ing WWE. In all four mixtures, the RNCB content was fixed at 6 wt% where the CF and WWE content were treated as variable. Mixtures containing WWE are given in the last four samples of Table 4.

2.3. Preparation of specimens

For the compressive strength test and ER measurements of the produced electrical conductive concretes, cylindrical specimen molds of 10 cm diameter and 20 cm height were used. Three cylinder specimens were produced for each mixture. For the flexural test of all mixtures, binary 10 × 10 × 40 cm prismatic specimens were produced. For the impact test, binary 10 × 10 plate specimens of 3 cm thickness were obtained from each mixture. After 24 h, all the specimens were removed from the molds and subjected to curing in a pool filled with drinking water for seven days. After curing, the heads of the cylinder specimens were cut 1 cm from the top by cutting machine to remove roughness for good contact in the ER measurements.

2.4. Test methods

2.4.1. Mechanical test methods

The compressive strength of the ECON produced was made on cylindrical specimens of 10 cm diameter and 20 cm height. A universal laboratory test device with the capacity of 250 tons was used to determine the compressive strength. Flexural strength tests of 10 × 10 × 40 cm prismatic specimens were performed with 5 tons flexural test device.

2.4.2. Impact test method

Impact states can be divided into two classes namely high and low speed impact [55]. The proposed impact test in the ACI 544.2R-89 [56] standard is the most appropriate test method for measuring the impact strength of a cementitious material plate. In this method, a cylinder specimen of 152 mm diameter and 63.5 mm thickness was used. At the center point of the specimen, the ball of 63.5 mm diameter is held constant. On the steel ball, a mass which weighs 4.54 kg is dropped from a height of 45.7 mm. In order to obtain the amount of energy that the specimen has absorbed against the impact, the dropping process repeats until the specimen breaks. The amount of absorbed energy according to the number of repetitions is calculated from Eqs. (1) and (2) given below.

$$e = m \times g \times h \tag{1}$$

$$E_u = N_u \times e \tag{2}$$

Here, e = Absorbed energy (Joules) for each impact, m = Weight of the mass, g (gravity) = 9.81 m/s^2, h = Drop height of the mass, Eu = Ultimate energy absorbed, N = Impact number.

Size and thickness limitations of specimens are one of the disadvantages of ACI 544.2R-89 impact method. Also, the use of a 4.54 kg steel as a drop-off mass is another disadvantage of this method, as the specimens having low energy absorption capacity will fail during the first drop. There are some studies related to the impact tests in the literature [55,57,58]. For example, Yahaghi et al. have studied the impact resistance of 10 × 10 cm plate specimens of different thicknesses by dropping steel balls of different weights on specimens [55].

In this study, 10 × 10 × 3 cm plate specimens were produced for impact tests. For the realization of the experiment, the impact tool designed in the laboratory was used. In this experiment, plate specimen is placed on the square-shaped support located at the bottom of the instrument. From the height of 45 cm, a mass of 1.1 kg is dropped to the center of the specimen. The impact process continues until the final crack occurs in the specimen.

2.4.3. Electrical resistance measurement test methods

Electrical resistance of the produced concretes were measured using standard cylinder specimens of 20 cm height and 10 cm diameter. The resistance of the electrical conductive concrete can be measured by different methods. In this study, the current values passing through concrete specimens were measured by two different methods, namely bulk and Wenner Prop methods. Descriptions of these methods were given below:

1. Bulk (Two-probes) method: In this method, a specific potential difference is applied between the two surfaces of the specimen (Fig. 1). As a result of the applied voltage, electrical current between two surfaces of the specimen is measured. Electrical resistance of the specimen is then measured using the Eqs. 3–5 [5,12].

$$V = IR\,(V) \tag{3}$$

$$R = \frac{V}{I}\,(\Omega) \tag{4}$$

$$\rho = R\frac{A}{L}\,(\Omega.cm) \tag{5}$$

Here V, I, R and ρ denotes applied voltage, current, resistance of specimen and resistivity of specimen respectively.

2. Wenner Probe (Four-probes) method: In this method, resistance measurement takes place by applying voltage to the four-probes equipment that is in contact with the surface of a cylinder specimen. The apparatus with four-probes used in this study is given in Fig. 1. In this apparatus, a certain potential difference between two internal probes is applied and the amount of current between the two external probes is measured. The resistance is calculated from Ohm's law (Eq. (4)) and the superficial resistivity of the specimen is obtained using equation (6) [59,60].

$$\rho \ = 2.\pi.a.R \tag{6}$$

Here, ρ is the resistivity of the specimen, a, distance between probes and R, the resistance of the specimen.

2.4.4. Microstructure characterization

After the compressive strength test, SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive X-Ray Spectroscopy) analysis were performed to examine the microstructure of the specimens and elemental compositions in their internal structure.

3. Result and discussion

Electrical, mechanical and impact properties of specimens produced from different mixtures were investigated and all results are given in Table 5. As seen in the tables, all fillers used in conductive concretes has a positive effect on the reduction of electrical resistance where the level varies.

Filler materials used to increase the conductivity had not adverse effects on the mechanical properties of concretes. All results are graphically detailed in the below sections.

3.1. Mechanical test results

3.1.1. Compressive test results

The compressive values of the electrically conductive concretes were compared according to RNCB, CF and SF contents and are given graphically in Fig. 2. In the tests, the compressive strength of the control concrete specimen was determined as 44.15 MPa.

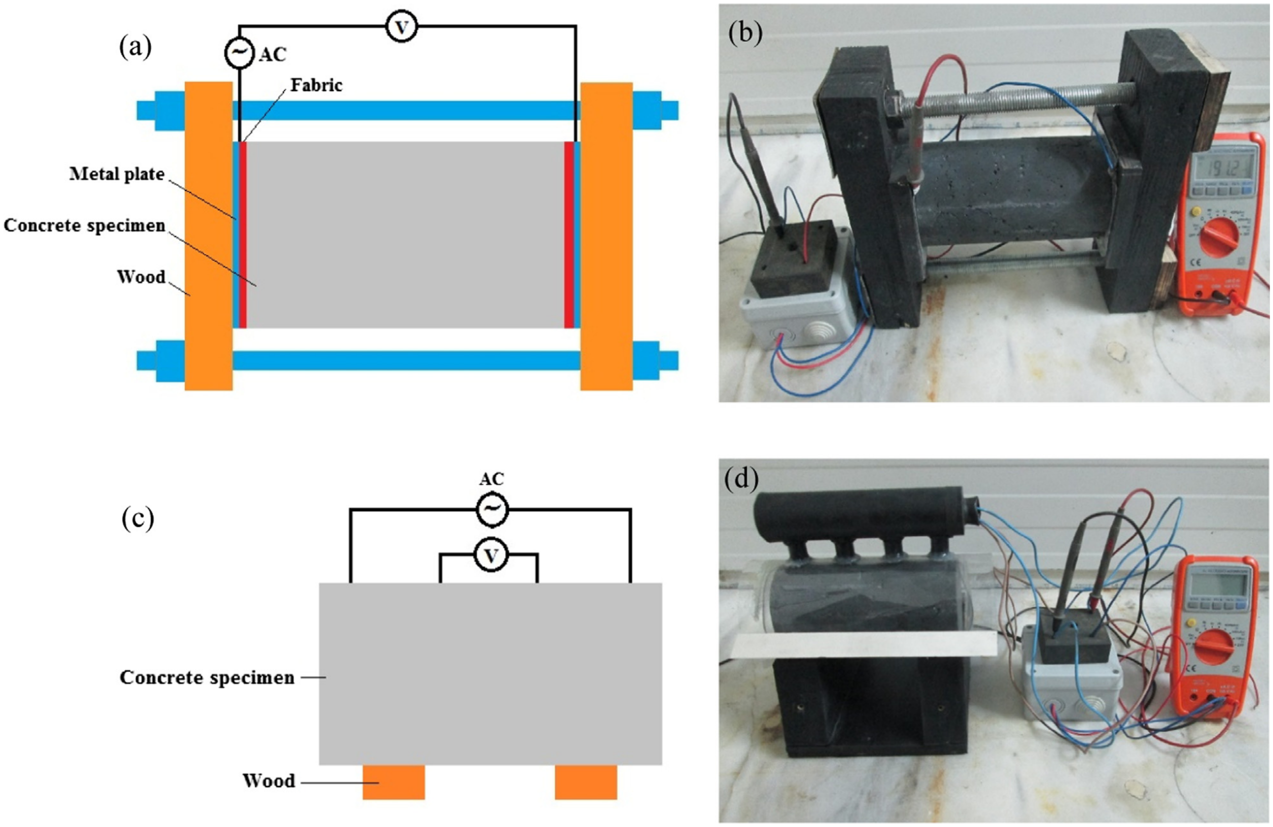

Fig. 1. Electrical resistance measurement equipments; (a) Bulk method-schematic, (b) bulk method-real (c) Wenner Probe method-schematic, (d) Wenner Probe method-real.

Table 5
28 Day, electrical, mechanical and impact test results.

No	Mixture code	BR (Ω.cm)	SR (Ω.cm)	σ_c (Mpa)	σ_f (Mpa)	Eu (J)
1	Control	22496.10	95209.00	44.15	4.98	22.66
2	N3C0S0*	22496.10	93483.00	44.45	6.33	27.52
3	N6C0S0	25524.42	94950.84	49.28	6.88	24.28
4	N10C0S0	23491.50	95845.32	52.26	6.42	24.28
5	N0C0.2S0	19376.20	93005.76	51.85	5.69	29.14
6	N3C0.2S0	13012.45	46844.81	54.20	6.59	59.89
7	N6C0.2S0	8400.44	32257.69	53.71	7.08	58.27
8	N10C0.2S0	4915.81	24185.80	51.04	7.75	79.31
9	N0C0.5S0	1629.55	8799.58	48.15	8.17	76.08
10	N3C0.5S0	1438.77	4316.31	45.56	7.71	90.64
11	N6C0.5S0	222.45	560.58	45.49	7.63	72.84
12	N10C0.5S0	385.78	1444.35	42.16	8.13	66.36
13	N0C1S0	175.80	569.59	48.66	8.55	45.32
14	N3C1S0	113.03	321.46	48.86	9.30	46.94
15	N6C1S0	80.08	188.34	47.82	8.62	55.03
16	N10C1S0	97.24	246.20	53.37	8.74	53.42
17	N0C0S2	7807.47	38412.75	48.51	6.53	132.73
18	N3C0S2	5898.98	32562.35	47.11	9.02	165.10
19	N6C0S2	5218.62	28180.55	44.52	8.70	160.25
20	N10C0S2	6824.01	20472.03	50.76	8.71	153.77
21	N0C0.2S2	7830.50	19732.86	47.79	7.20	152.15
22	N3C0.2S2	6290.38	21135.67	51.18	6.35	155.39
23	N6C0.2S2	6538.27	24322.38	50.85	6.70	152.15
24	N10C0.2S2	3979.82	16237.66	54.54	6.26	142.44
25	N0C0.5S2	2708.71	13261.86	55.07	7.02	192.62
26	N3C0.5S2	1098.73	4113.66	56.33	8.15	186.14
27	N6C0.5S2	696.18	2673.34	56.99	8.12	200.71
28	N10C0.5S2	940.33	3452.88	55.15	7.62	203.95
29	N0C1S2	95.83	276.00	50.40	7.62	205.57
30	N3C1S2	77.39	195.03	52.84	7.91	218.52
31	N6C1S2	85.22	194.30	62.01	8.68	234.70
32	N10C1S2	305.47	916.41	62.23	9.31	249.27
33	N6C0W0.5*	1676.55	6352.45	52.24	7.09	192.62
34	N6C0W1.0	1546.33	5720.20	57.87	7.68	236.32
35	N6C0.2W1.0	376.53	1097.12	41.82	7.58	265.46
36	N6C0.2W1.5	129.48	441.18	39.52	7.21	254.13

*N: Recycled Nano Carbon Black, C: Carbon Fiber, S: Steel Fiber, W: Waste Wire Erosion.

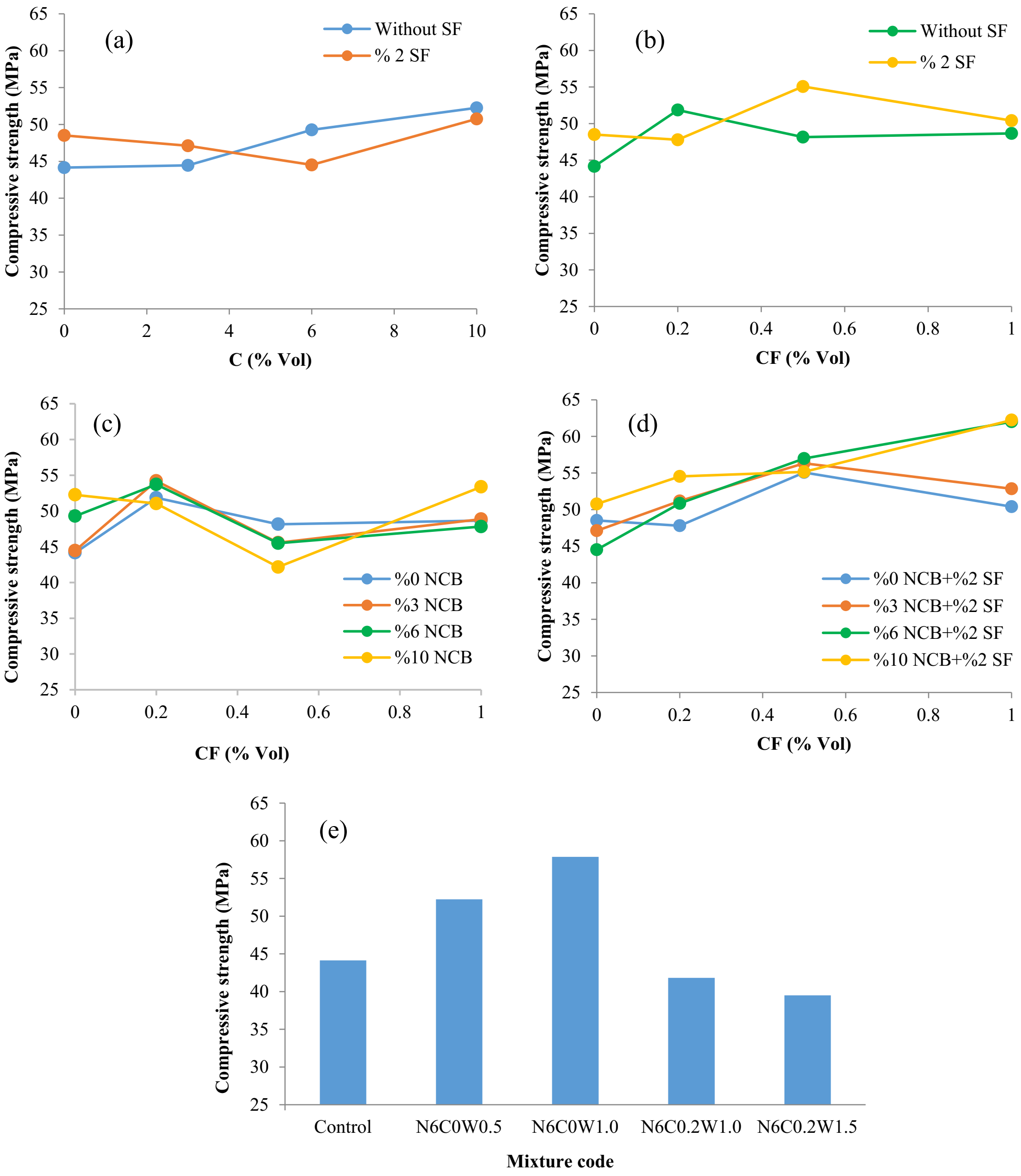

Fig. 2. Effects of RNCB, CF and SF content on compressive strength.

The compressive strength of the specimens containing pure RNCB were increased continuously with the increase of the RNCB content and the maximum compressive strength was obtained as 52.26 MPa when using 10 wt% RNCB. When 2 wt% SF was added in mixtures containing RNCB, there was no improvement in the compressive strength of the mixtures containing 0–6 wt% RNCB, but when the SF ratio increased to 10 wt%, the compressive strength increased to 50.76 MPa (Fig. 2-a). CF didn't positively affect the compressive strength of electrically conductive concretes. However, the compressive strength of the specimen containing 0.2 vol% CF was greater than the others, with 51.85 MPa value. The compressive strength of the concrete containing 0.1–1 vol% CF with similar mixture design was found to be 45–55 MPa [5]. When CF was used with SF, it had no negative effect on compressive strength. In this case, the maximum compressive strength was found to be 55.07 MPa when using 0.5 vol% CF (Fig. 2-b).

As shown in Fig. 2-c, there was no significant improvement in compressive strength when RNCB and CF were used together. In this mixture group, the minimum compressive strength (42.16 MPa) belongs to the specimen containing 0.5 vol% CF and 10 wt% RNC. It was determined that the maximum compressive strength (53.37 MPa) belongs to the specimen containing 1 vol% CF and 10 wt% RNCB.

The compressive strengths of electrical conductive concretes containing CF, RNCB and SF are shown in Fig. 2-d. No regular strength increase was observed in RNCB-free specimens, however, in all mixtures containing RNCB-CF-SF, the compressive strength increased with increasing CF. The effect of RNCB ratio is seen more clearly from the figure. The compressive strength was higher in mixtures containing 2 wt% SF and 6–10 wt% RNCB. The maximum compressive strength (62 MPa) in this mixture group belongs to the specimen containing 1 vol% CF.

The compressive strength of conductive concrete specimens containing RNCB, CF and WWE are given in Fig. 2-e. In CF-free specimens, compressive strength increased with increasing of WWE from 0.5 to 1 vol%. At the same time, the compressive strength of these two specimens increased compared to the control specimen. Addition of 0.2 vol% CF to mixtures containing 1 vol%

WWE caused the compressive strength to be reduced from 57.87 to 41.82 MPa. In specimens containing 6 wt% RNCB and 0.2 vol% CF, no significant difference was observed between the compressive strengths when 1 vol% and 1.5 vol% WWE were used. The specimen containing 6 wt% RNCB and 1 vol% WWE in this mixture group showed maximum compressive strength as 57.87 MPa. Minimum compressive strength (39.52 MPa) was observed in the specimen containing 6 wt% RNCB, 0.2 vol% CF and 1.5 vol% WWE.

3.1.2. Flexural test results

The positive effect of RNCB in terms of flexural strength on concrete can be seen in Fig. 3-a. The flexural strength of the control concrete specimen was found to be 4.98 MPa, which increased to 6.88 MPa by adding 6 wt% RNCB to the mixture. Also, a significant increase in flexural strength was observed when different ratios of RNCB were added to the mixtures containing 2 wt% SF. In this case, the maximum flexural strength was obtained as 9.02 MPa for the specimen containing 3 wt% RNCB.

The effect of CF on the flexural strength can be seen in Fig. 3-b. With the increase of CF ratio in concrete specimens containing only CF, flexural strength was increased and maximum strength was obtained as 8.55 MPa for specimen with 1 vol% CF. The flexural strength of the concrete specimen containing 2 wt% SF was 6.53 MPa, while the strength increased to 7.62 with a slight slope when the CF was added at different rates.

The flexural strength of the conductive concretes with different ratios of CF were investigated according to RNCB content and are given in Fig. 3-c. When 3%, 6% and 10 wt% RNCB were added, the flexural strengths were obtained between 6 and 9 MPa, which did not change significantly compared to mixtures containing only CF.

In Fig. 3-d, the effect of RNCB, CF and SF (three-in-one) on the flexural strength of conductive concretes in different mixtures were investigated. The flexural strength of the specimen containing 2 wt% SF and different ratios of CF were varied between 6 and 8 MPa. When RNCB was added to mixtures containing 2 wt% SF and different ratios CF, the flexural strength of specimens con-

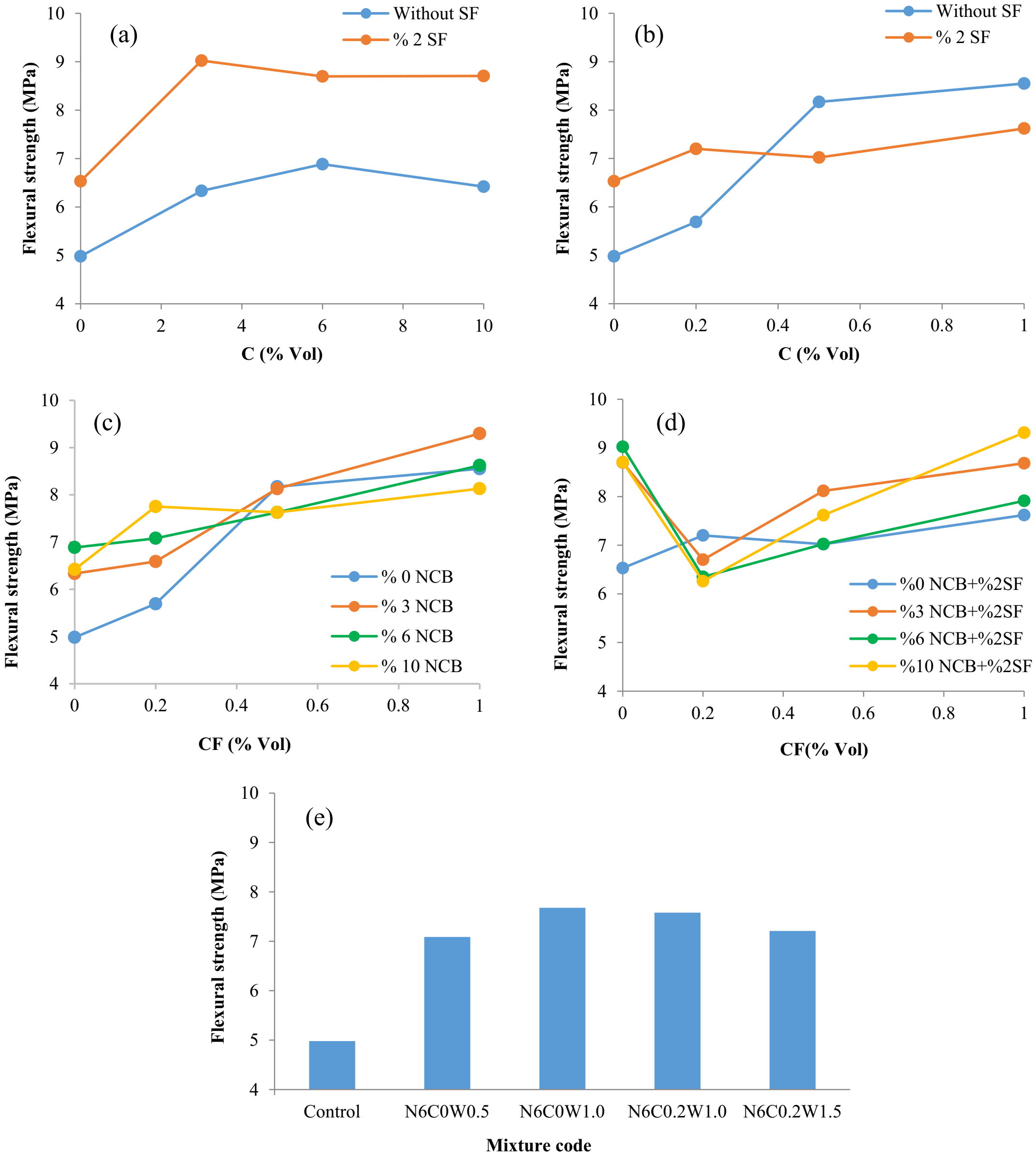

Fig. 3. Effects of RNCB, CF and SF content on flexural strength.

taining 0.2 vol% CF in all mixtures decreased to 6–7 MPa. However, this value increased to 8–9 MPa with the increase of CF.

The flexural strengths of all conductive concrete specimens containing RNCB, CF and WWE were improved compared to the control specimen (Fig. 3-e). However, there was no significant difference between the flexural strength of the specimens obtained from these mixtures. Flexural strength of this mixture group was obtained as 7.09–7.68 MPa.

3.2. Impact test results

Impact energies absorbed by the conductive concretes with different mixtures are presented in Fig. 4. No significant difference was found in terms of impact energy between RNCB-containing specimens and control specimen. Ultimate absorbed energy values were calculated between 22 and 27 J. Ultimate absorbed energy values of the same mixture with 2 wt% SF additives were calculated between 132 and 165 J ,where 165 J obtained for the mixture containing 3 wt% RNCB (Fig. 4-a).

Ultimate impact energy values of conductive concretes containing CF with three different ratios are given in Fig. 4-b. When CF ratio increased to 0.5 vol%, absorbed energy increased to 76 J, then decreased to 45 J. Ultimate energy values of conductive concretes containing CF with 2 wt% SF were found to be increased from 130 to 205 J when CF content was increased from 0 to 1 vol%.

The effect of RNCB on absorbed energy against impacts by conductive concretes containing different CF ratios is given in Fig. 4-c. When RNCB is added to conductive concretes containing CF, maximum absorbed energy was obtained for specimen containing 0.5 vol% CF and 3 wt% RNCB. In general, maximum impact energy values of all RNCB doped specimens are associated with specimens containing 0.5 vol% CF.

In Fig. 4-d, ultimate energy values absorbed by the three-phase electrically conducting concretes are compared. By increasing CF ratio in conductive concretes containing both SF and RNCB, ulti-

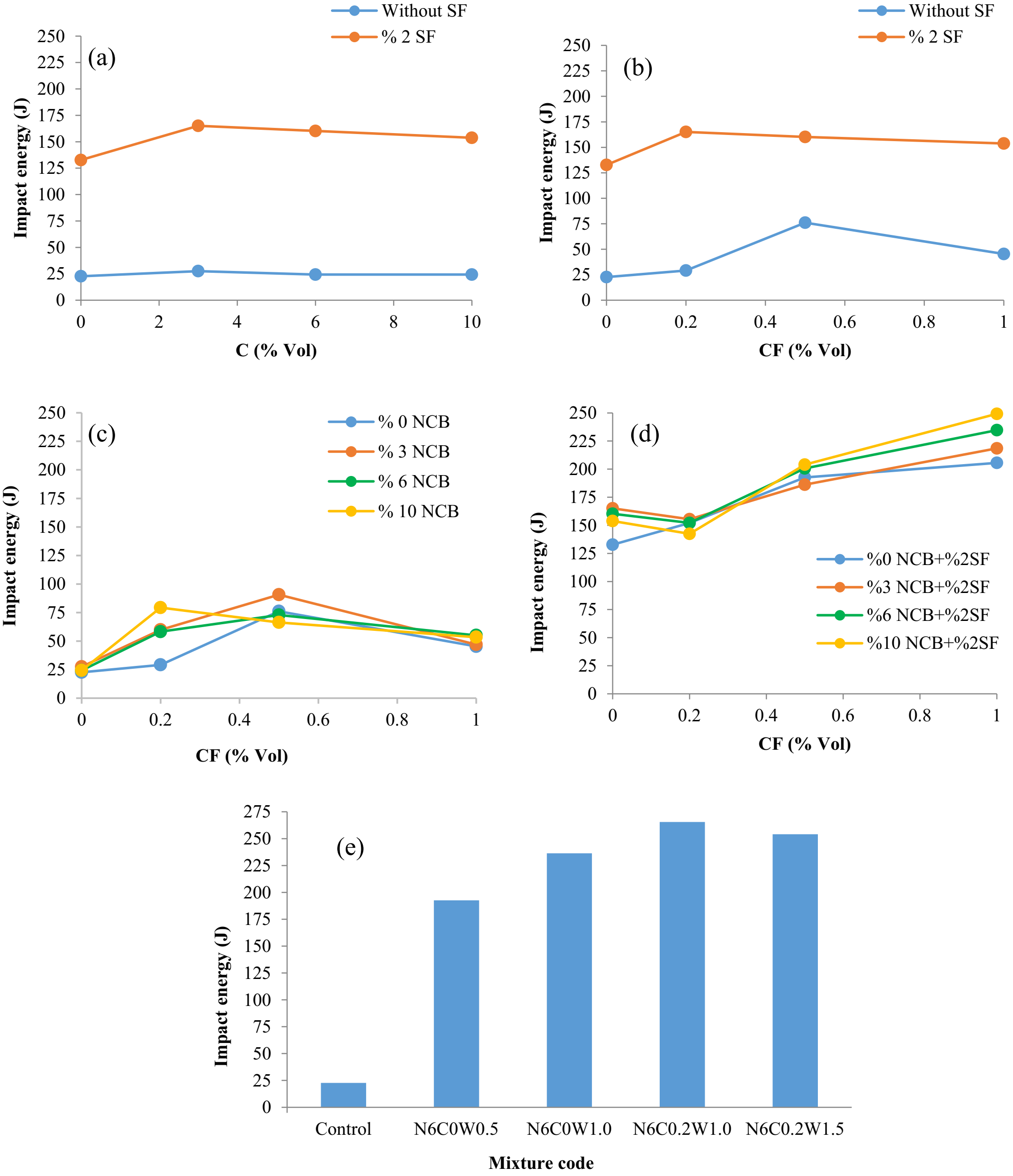

Fig. 4. Effects of RNCB, CF and SF content on impact energy.

mate energy amount has increased continuously. According to Fig. 4-d, the specimen containing 10 wt% RNCB and 1 vol% CF has maximum absorbed energy.

The amount of energy absorbed by all conductive concretes containing WWE has increased by more than 10 times compared to control specimen (Fig. 4-e). As the WWE content increased, the impact energy increased for all specimens except the specimen containing 0.2 vol% CF and 1.5 vol% WWE where few reduction observed. The maximum impact energy (265.46 J) in this group was obtained for the specimen containing 6 wt% RNCB, 0.2 vol% and 1 vol% WWE.

3.3. Electrical test results

3.3.1. Bulk resistance (BR)

When only RNCB was used in the mixes, there was no change in the electrical resistance reduction according to the obtained BR values, and even with the increase in the RNCB ratio, it has been observed that the BR values have only slightly increased (Fig. 5-a). El-Dieb et al. [12] found that the use of carbon powder alone had no significant effect on electrical conductivity. It was observed that the BR values were decreased more than three times when 2 wt% SF were added to these mixtures. Among the specimen results with RNCB and 2 wt% SF, minimum BR value (5218.62 Ω.cm) was obtained with the specimen having belongs to the specimen containing 6 vol% RNCB.

The effect of CF on concrete, has also emerged when used at low rates, however, as shown in Fig. 5-b, when the content of CF was higher than 0.5 vol%, the BR values have decreased at higher speed. When CF and 2 wt% SF were used together, it was found that the BR values was reduced approximately 2 times compared to the specimen results containing only CF, but in mixtures containing 0.5 vol% and 1 vol% CF, SF was showed side effect in reducing electrical resistance.

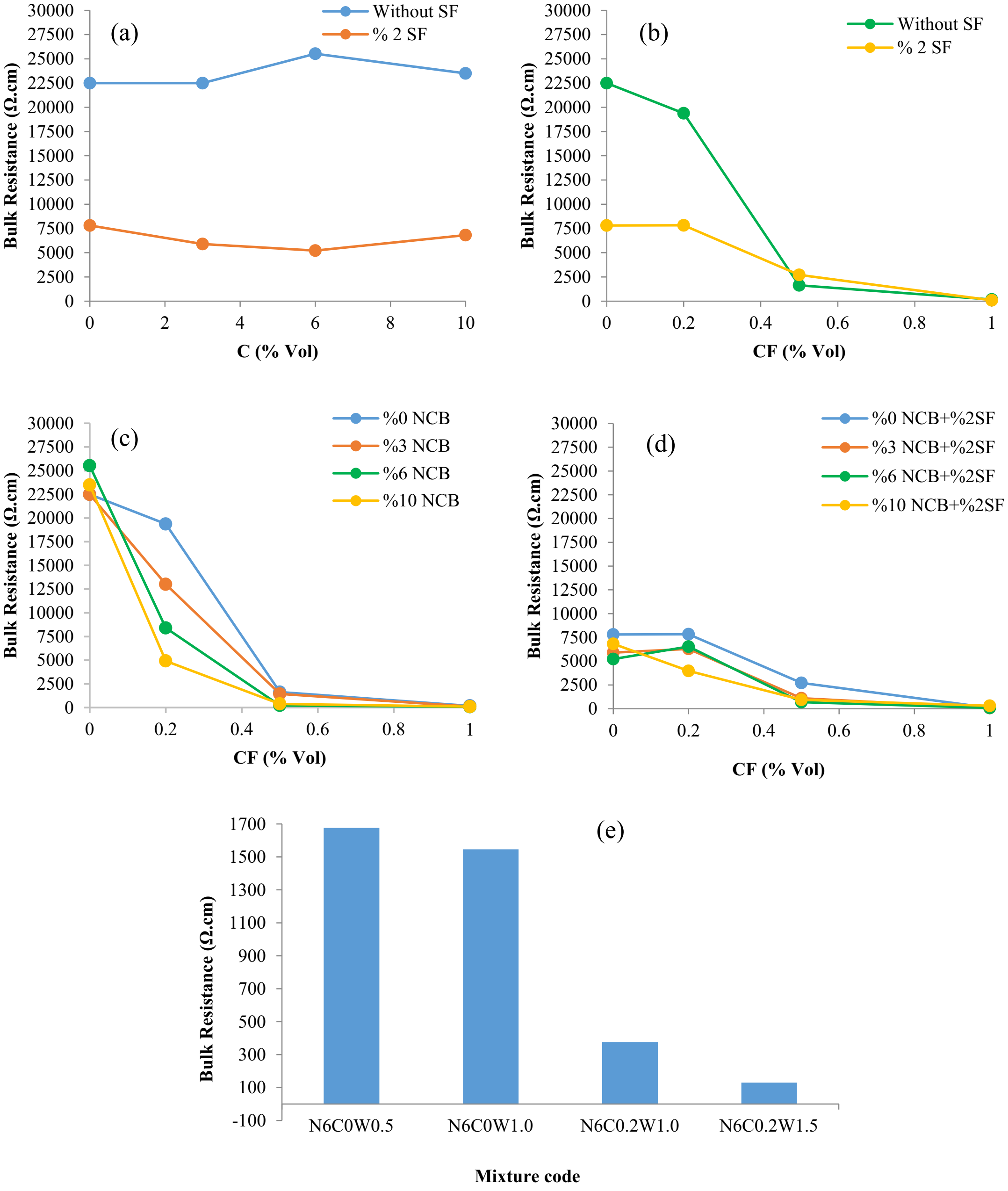

Fig. 5. Effects of RNCB, CF and SF content on BM-Resistance.

In Fig. 5-c, the effect of RNCB ratio on BR was investigated in mixtures containing different ratios of CF. This is particularly evident in specimens containing low amounts of CF, i.e. 0.2 vol% at first degree and 0.5 vol% at second degree. With the increase of CF content, the effect of RNCB on BR was decreased. The lowest BR values were obtained from this mixture group. The BR value of the specimen containing 6 wt% RNCB-0.5 vol% CF was measured 222.45 Ω.cm, and the BR value of the specimen containing 6 wt% RNCB-1 vol% CF was 80.08 Ω.cm. In the Sassani et al. [5] study, the minimum resistance of the mixture containing only 1 vol% CF was obtained as 800 Ω.cm.

The BR values of three-phase electrically conductive concretes are summarized as graphs in Fig. 5-d. When the RNCB is used at all three ratios, BR values were significantly reduced. BR values of all specimens containing 0.5–1 vol% CF decreased faster. In addition, the change in the RNCB ratio in three-phase electrical concrete has no effect on the reduction of electrical resistance.

The electrical resistance of all four mixtures containing WWE was measured below 1700 Ω.cm, both when using CF and without use (Fig. 5-e). Whereas, the BR of the control specimen was measured above 22000 Ω.cm (Table 5). This shows how effective WWE is in reducing electrical resistance. However, in the RNCB additive mixtures, the BR values were measured between 100 and 400 Ω.cm when WWE and CF were used together. Among the mixtures containing WWE, the lowest BR value was obtained as129.49 Ω.cm for the mixture containing 6 wt% RNCB, 0.2 vol% CF and 1.5 vol% WWE.

3.3.2. Surface resistance (SR)

SR values of conductive concretes, containing RNCB-SF and CF-SF, measured by Wenner Probe method are given in Fig. 6-a. When

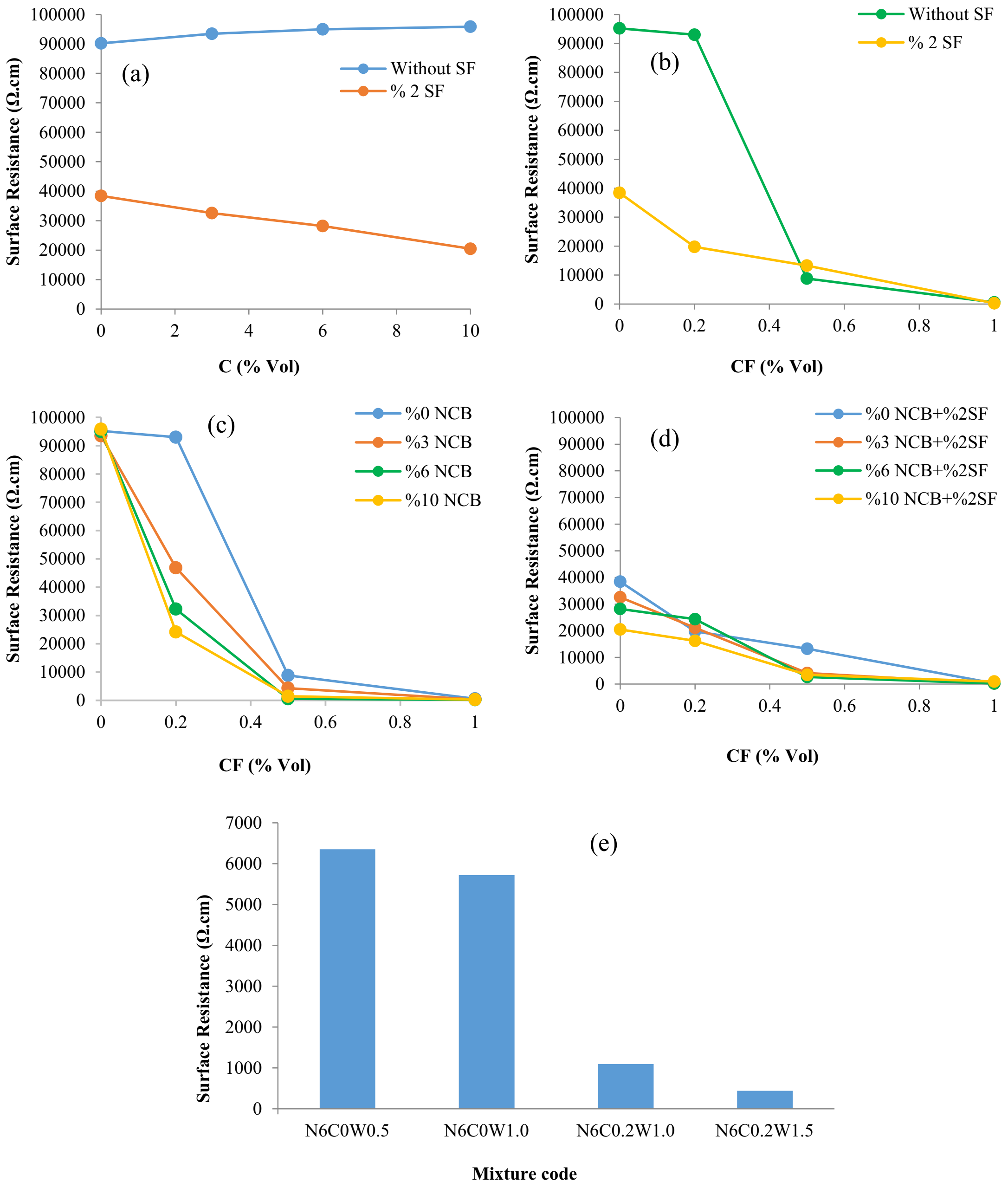

Fig. 6. Effects of RNCB, CF and SF content on WPM-Resistance.

the resistance measured with this method are compared with BR values, a similar slope in the graphs were observed. However, all resistance values measured in this method are approximately 4 times higher than BR values. In this method, similar to the two-point uniaxial method, the electrical resistance of the specimens was reduced more than twice with the addition of SF. In addition, in specimens containing CF, resistance was decreased rapidly with increasing CF content (Fig. 6-b). In this group, SR values of conductive concretes containing 1 vol% CF and 1 vol% CF-2 wt% SF were lower compared to the other mixture results.

SR values of electrically conducting concrete with different ratios of CF decreased with increasing CF content (Fig. 6-c). In addition, the effect of CF was increased by 3–15 times when RNCB was added to the conductive concretes obtained from the same mixtures. The SR value of the specimen containing 0.2 vol% CF was 95005 Ω.cm, and this value decreased by ten times to 8995 Ω.cm by adding 3% RNCB. SR values of specimen containing 0.5 vol% CF and 6 wt% RNCB were measured as 560.58 Ω.cm with a 15-fold decrease compared to the specimen containing only 0.5 vol% CF. For specimen group containing CF-RNCB, the minimum SR value belongs to the specimen containing 1 vol% CF-6 wt% RNCB at 188.34 Ω.cm.

When CF, RNCB and SF were used together, the best SR results were found to be associated with mixtures containing 3–10 wt% RNCB, 1 vol% CF and 2 wt% SF (Fig. 6-d). SR value was obtained as 194.30 Ω.cm for the specimen containing 6 wt% RNCB-1 vol% CF. In this group, RNCB influenced the mixture more than others in specimens containing 0.5 vol% CF.

SR values of mixtures containing WWE were measured between 6352.45 and 441.18 Ω.cm (Fig. 6-e). 6352.45 Ω.cm for 6 wt% RNCB-0 vol% CF-0.5 vol% WWE mixture and 441.18 Ω.cm for 6 wt% RNCB-0.2 vol% CF-1.5 vol% WWE mixture. As in the BR, SR were affected by the rate of WWE.

3.4. SEM results

As shown in the SEM images of Fig. 7-a, the cement paste in the inner structure of the concrete consists of pores and cement products. In Fig. 7-b, in the internal structure of the specimen containing 6 wt% RNCB, it can be seen that the cement products are increased relative to the control specimen. During the specimen production, it was found that the carbonized mixtures had higher gel-forming behavior compared to carbon free mixtures. This behavior is more pronounced in CF doped mixtures. In other words, the addition of CF to the mixture resulted in the reduction of the cement paste and the difficulty of the workability. This, as can be seen in the Fig. 7-c SEM image, may cause intervals of CFs to remain porous. The homogeneous distribution of RNCB in the cement paste and thus the increase of the interface area between the CF-cement can be seen from Fig. 7-d. Increasing the contact area can lead to improved adhesion between the fiber and concrete.

4. Conclusions

The evaluation of the waste recycled nano carbon black and the waste wire erosion in electrically conductive concrete were investigated. For this, mechanical, impact, bulk resistance and surface resistance of the concretes were investigated. The results are summarized below:

- The compressive strength of all mixtures containing RNCB were improved. When CF and SF were used together, there was no significant improvement in compressive strength. The addition of CF to mixtures containing RNCB did not have a significant effect on compressive strength. On the other hand, RNCB never affected the resistance of concrete when used solely. The

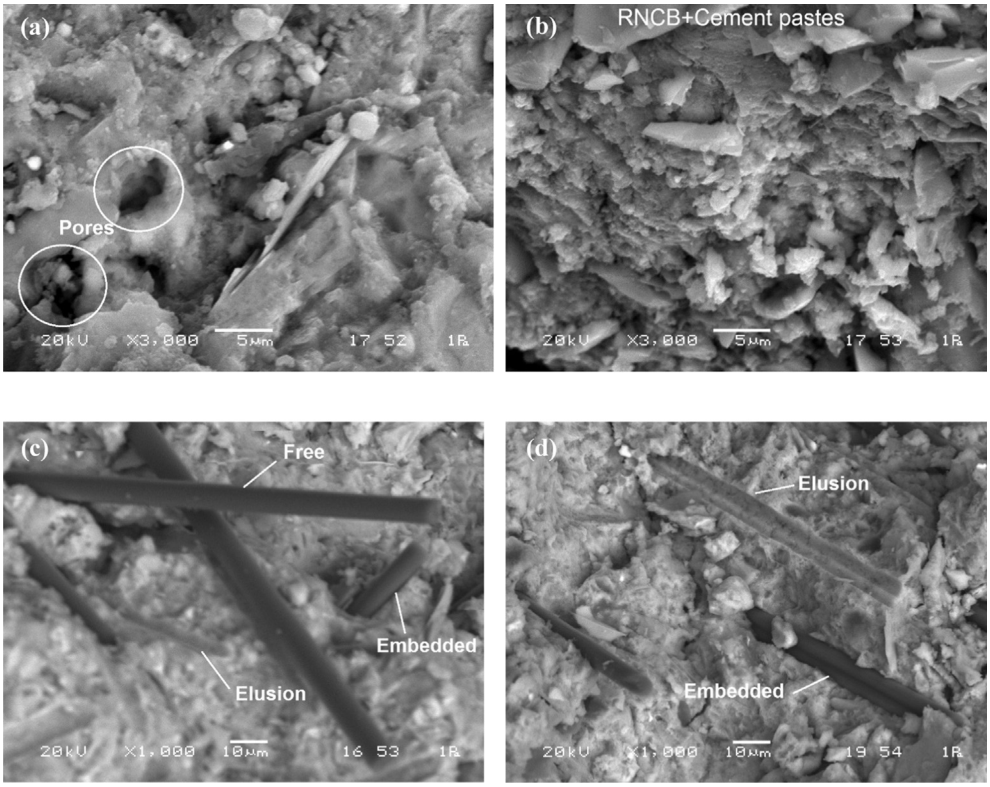

Fig. 7. SEM images of specimens; a) control specimen, b) specimen containing 6 wt% RNCB, c) specimen containing 0.5 vol% CF, d) specimen containing 6 wt% RNCB – 0.5 vol% CF.

addition of RNCB to CF and SF-containing concretes had significant benefits on the reduction of resistance. In general, best results were obtained in the specimens containing 6 wt% RNCB.

- There was no improvement in compressive strength when CF was used alone over 0.5 vol%. This, can be explained by the reduction of cement paste, reduction of workability and reduction of the adhesion surface by increasing the CF ratio. This can be clearly seen in the SEM images. At the same time, CF was the most effective additive for reducing electrical resistance when used alone and in combination with other fillers.
- In concretes containing 6 wt% RNCB, there was an improvement in the compressive strength when 0.5–1 vol% WWE was added. However, when WWE and CF are used together, the compressive strength was reduced compared to the control specimen. WWE, had a significant effect on the reduction of electrical resistance, especially when used in combination with 0.2 vol% CF, low resistance as 129 Ω.cm was obtained.
- When all the filling materials used were added to the concrete mixtures either one by one or together, they had positive effects on flexural strength. The RNCB has substantial role in improving the mechanical property by increasing the binding property of the concrete as it is evident from the mixture order and results of SEM analysis.
- All three fibers used were increased the resistance of the conductive concrete against impact. WWE ,SF and CF were increased about ten and three times respectively. Although RNCB alone had no effect on impact energy, it was useful when used in combination with CF, SF and WWE.
- RNCB and WWE, which are used as waste materials for the purpose of increasing the conductivity in different mixtures, have been successfully increased the conductivity. The costs of N0C1S0, N6C0.5S0 and N6C0.2W1.5 mixtures whose electrical resistance was similar were calculated as 914.95, 517.38 and 576.93 $, respectively. In other words, to achieve a certain conductivity, adding 6 wt% RNCB to the mixture containing 0.5 vol% CF reduces the cost by 43%, likewise, the addition of 6 wt% RNCB and 1.5 vol% WWE to the mixture containing 0.2 vol% CF lowers the cost by 37%.

Various materials for the development of electrically conductive concrete can still be evaluated [5]. In this study, the evaluation of two waste materials in electrically conductive concrete was discussed. Consisting of 36 mixtures, 28-day results of different characteristics were presented, which would be useful in future studies. For subsequent studies, it is recommended to examine the electrical conductivity and corrosion characteristics of these mixtures over a long period of time. The authors are conducting lab-scale heating tests of selected specimens produced in this study where the results will be reported.

Declaration of Competing Interest

There is no conflict of interest.

Acknowledgements

Authors wish to thank Sakarya University and Sakarya Applied Sciences Unıversıty for technical assistance along with the director of Sakarya INCI BETON for their support. This work was supported by Sakarya University Scientific Research Foundation, Project number: 2018-50-02-002.

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