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RESEARCH PAPER

The Effects of Cold-Drawn Crimped-End Steel Fibers on the Mechanical and Durability of Concrete Overlay

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ABSTRACT: A bonded concrete overlay consists of a new concrete overlay placed directly on top of an existing concrete pavement. The properties of such layer have a distinguished factor for reliable service-life extending of concrete pavements repairing systems. In this paper, the engineering properties of cold-drawn crimped-end steel fiber reinforced (CFCSF) concrete mixtures as overlays are evaluated. To this end, CFCSF mixtures are made with fiber contents of 15 and 25 kg/m^3 with diameters of 0.8 and 1 mm and water-cement ratio of 0.5 in comparison with reference concrete. The engineering properties of these types of concrete in the properties of the fresh and the hardened concrete including Compressive Strength (CS), Tensile Strength (TS), flexural strength (FS), Modulus of Elasticity (ME), depth of Water Penetration (WP), Impact (IR) and Abrasion Resistance (AR) are investigated. The results show that at an early age, the addition of fibers had no significant effects on the CS but at higher ages, the samples containing steel fibers have higher compressive TS and FS than the control ones. Also, the use of steel fibers increases the ME, IR and AR of CFCSF specimens. Moreover, models are developed to correlate the mechanical properties of mixtures with AR and IR. The comparison between the relation of AR and IR to other mechanical properties, made of the linear regression and polynomial relationships in aspects of R^2, indicates that stronger relations are available between TS with IR and AR with ME.

Keywords: Abrasion Resistance, Concrete Overlay, Impact Resistance, Mechanical Properties, Steel Fiber.

1. Introduction

Concrete overlays, are defined as a suitable solution which have long life and high durability, lead to fewer repairing and replacing cycles and lower related expenses, and fewer raw materials, energy, and resources used with the passage of time. Two options regarding concrete overlays exist: bonded and unbonded. Bonded concrete overlays are comparatively thin (50-150 mm). The overlay and the existing pavement when bonded, perform as one integrated system. To ensure a good performance, it is needed a strong bond between the pavement and overlay. Such

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bonded system ensures the load-bearing capacity of whole composite pavement system. (Harrington and Fick, 2014; Isla et al., 2015).

Nowadays, the technology developed in the field of pavement resurfacing systems. Many of the technological changes and advances predicted in previous studies have been realized because the pavement technologist and engineers cooperated to better design and present the required specifications for different types of concrete pavements.

Among recent developments, a better definition has been proposed to evaluate existing pavements for concrete pavements. A novel technique proposed, is the application of synthetic and steel fiber technology in this field. This technology has recently received a great attention due to the performance of thin concrete resurfacing. Fiber reinforcement increase the structural integrity of concrete attributed to the improved toughness and durability of the concrete. Some research studies have been carried out, providing solutions of bonded and un-bonded concrete overlays for road pavements (Isla et al., 2015).

Tavakoli et al. (2016) investigated the mechanical behavior of the fiber reinforce of SCC with steel and synthetics fibers. They found that, polyphenylene sulfide (PPS) and glass fibers can make better the mechanical performance like the flexural and the tensile strength, toughness and fracture performance of FRC concretes; although the compressive strength is declined due to application of fibers. Moreover, steel fibers significantly increased properties of absorbing the energy.

LaHucik et al. (2017) studied the mechanical properties of ordinary FRC with fiber-reinforced RCC using different types of fibers. They found that, the compressive, splitting tensile and flexural strengths increased at low fiber content, then decreased at a higher contents.

Jafarifar et al. (2016) studied the impact of cracks regarding shrinkage on the capacity of load bearing of RCC pavement with steel fibers (SFRRCCP). They found that by neglecting the impact of shrinkage, the SFRRCCP capacity is overestimated by approximately two times.

Madhkhan et al. (2012) studied the impacts of mixed PP fibers and steel fibers in roller compacted concrete containing a kind of Iranian pozzolan. They concluded that compressive strength improved with the increasing amount fibers. Also, the flexural strength reduce with the fiber content so long as indices of the toughness increased with the fiber content.

Sukontasukkul et al. (2019) presented a case study on applying steel fibers in RCC pavement. The experimental program includes the compression and flexural strength, density of the strain energy, toughness, and energy dissipation at various ages. The results demonstrated that the water and the density of mixtures reinforced with fiber were more than ones of normal RCC mixtures to a certain extent. The compression strength was decreased with an increase of fibers. Although, flexural strength, toughness, and residual strength increased significantly with applying steel fibers.

Fwa and Paramasivam (1990) studied the thin steel fibre composite overlay for the repair of surface-distressed concrete pavements. The experimental study utilized to investigate the properties of proposed composite overlays. They found that 1% steel fiber would satisfactorily in this regard, and proposed the preferable thickness of overlay.

Atis et al. (2009) presented relations among strength features including compressive and flexural, and abrasion resistance of polymer-based fibers and steel fibers reinforced with fly ash contained concrete. Various replacements of cementitious material and fiber (both steel and polypropylene) were studied. They suggested some models to relate the mentioned properties and compared them with their accuracies.

Zhang et al. (2004) investigated the

impact, toughness and other features like density, tensile and compressive characteristics, and elastic modulus, of both normal and lightweight aggregate concrete reinforced with fibers. Their study revealed that density and high compressive strength have beneficial effects on impact resistance, and the inclusion of the steel fibers substantially made better the impact strength.

Neves and Fernandes de Almeida (2005) studied the effects of strength of the cement matrix, the fiber content and the fiber diameter on the compression strength of steel FRC mixtures. They concluded that adding fibers to concrete enhances its energy absorption capacity, although it can moderately decrease the elastic modulus. Furthermore, analytical model proposed to estimate the stress–strain relationship for steel FRC in compression. The model results are compared with experimental stress-strain curves.

Ramezani and Esfahani (2018) evaluated the effects of hybrid FRC against the freezing/thawing action. The elite mixtures (steel fibers with the amount of 0.75% and PP fibers with the amount of 0.4%) showed the highest freezing/thawing scaling resistances as the materials which were scaled in this mix were approximate half of scaled materials from the normal mixture after cycling of freezing/thawing.

Song et al. (2004) presented a statistical model for the resistance against impact regarding steel-FRC with two fiber volumes, in comparison with ordinary samples. The results revealed that density and high compressive strength are favorable for this purposes.

Shadafza and Jalali (2016) investigate the elastic modulus of SFRC. Results showed that random distribution of fibers and aggregate and the lack of the homogeneity of the matrix have great effects in this content.

Thus, present research purposes to study effects of cold-drawn crimped-end steel fiber reinforced (CFCSF) on the behavior of concrete mixtures. To this end, CFCSF mixtures were made with fiber contents of 15 and 25 kg/m^3 with diameters of 0.82 and 0.99 mm and water - cement ratio of 0.5 compared to reference concrete. To interpret the trends of results, regression models would be developed and compared.

2. Material and Methods

2.1. Materials

An ordinary Portland cement type II, which was locally available is conforming provisions of ASTM C150 (2019). The physical and chemical features of the cement utilized for this study are presented in Table 1.

Limestone aggregates were locally provided from available sources. The coarse aggregates (coarse and fine gravel) were consumed had following features of maximum size of 19 mm and a saturated surface dry specific gravity of 2520 kg/m^3 and water absorption percentage of 1.8. The river sand was also consumed which had the specific gravity of 2570 kg/m^3. The sand water absorption was obtained 2.9%. Their SSD gravity was 2635 kg/m^3. The utilized steel fibers are of cold-drawn crimped-end steel fiber type conforming Type I ASTM A820 (2016) as presented in Table 2.

2.2. Mixture Proportion

Table 3 presents a summary of proportions of the concrete mixture. Furthermore, the control concrete without natural steel fibber (SW), four mixtures were made by using 0.83 and 0.99 mm diameter fiber with 15 and 25 kg/m^3 fiber.

2.3. Preparing Specimens

At first, Materials in dry form were mixed together, after that water was added into the mix. Afterwards, the steel fiber was added to the mixture if available. The mixed concrete was poured into the mold immediately, and consolidated by using a shaking table. After molding, all of samples were left covered during next 24 hours in the casting room. Henceforth, experimental specimens were demolded and cured at 23

± 1 °C and a moist situation during the determined age for every test according to the ASTM C192 (2019).

3. Discussions of Experimental Results

3.1. Fresh Characteristics

The fresh characteristics of the mixed concrete including density and air content are depicted in Table 4.

3.2. Mechanical and Durability Tests

To evaluate the properties of CFCSF mixtures, mechanical and physical tests including the tensile and compressive strength, flexural strength, impact resistance, elastic modulus, water penetration depth and abrasion resistance carried out as following methods:

3.2.1. Compressive Strength

The compression strength of the mixed concrete was determined for cubic specimens of 150×150×150 mm and the results are reported in Table 5 for 7-day, 28-day and 56-day compressive strength.

3.2.2. Tensile Strength

The tensile strength of the mixtures evaluated via ASTM C496 (2014) at 7-day, 28-day and 56-day, are presented in Table 6.

Table 1. Features of the cement utilized in this study

Compound/ Property	Cement Type II
Chemical analysis, %	
Calcium oxide (CaO)	61.68
Silica (SiO_2)	22.58
Alumina (Al_2O_3)	4.45
Iron oxide (Fe_2O_3)	4
Magnesium oxide (MgO)	3.05
Sodium oxide (Na_2O)	0.48
Potassium oxide (K_2O)	0.4
Sulfur trioxide (SO_3)	1.71
Other properties	
3-day compressive strength, MPa	17.8
7-day compressive strength, MPa	26.2
28-day compressive strength, MPa	38.4
Initial time of setting, min	164
Final time of setting, min	245
Specific gravity (g/cm^3)	3.15
Specific surface, m^2/gr	2805
Loss on ignition (975°C)	1.07

Table 2. Features of utilized steel fibers

Name	Diameter (mm)	Length/Area ratio	Tensile strength (MPa)
CFCSF8	0.82	0.51	1220
CFCSF10	0.99	0.79	1201

Table 3. Proportions of concrete mixture $^+$

Mixture identification	Definition	Steel fiber (kg/m^3)	Cement (kg/m^3)	Coarse aggregate* (kg/m^3)	Fine aggregate* (kg/m^3)	Water (kg/m^3)
SW	Reference	-	350	850	960	175
SW0.8-15	0.83 mm fiber	15	350	850	960	175
SW0.8-25	0.83 mm fiber	25	350	850	960	175
SW1.0-15	0.99 mm fiber	15	350	850	960	175
SW1.0-25	0.99 mm fiber	25	350	850	960	175

$^+$ w/c ratio = 0.5, * SSD condition

Table 4. Fresh characteristics of the mixed concrete

Mixed concrete identification	Density (kg/m^3)	Air content (%)
SW	2345	1.5
SW0.8-15	2365	2.4
SW0.8-25	2375	2.6
SW1.0-15	2369	2.5
SW1.0-25	2380	2.7

3.2.3. Flexural Strength

The flexural strength of the mixtures evaluated via ASTM C78 (2018) at 7-day, 28-day and 56-day, are given in Table 7.

3.2.4. Modulus of Elasticity

The modulus of elasticity of mixtures was calculated via ASTM C469 (2014) at 28-day, are reported in Table 8.

3.2.5. Impact Resistance

The resistance against impacts for mixtures was measured by drop-weight test method mentioned in ACI 544.2R (1989) at 28 day and presented in Table 9.

3.2.6. Depth of Water Penetration

The water penetration depth of the specimens was determined based on BS EN 12390-8 (2019) at 28-day and 56-day and presented in Table 10.

3.2.7. Abrasion Resistance

The resistance against abrasion of mixture surfaces was determined according to ASTM C779 (2019) (procedure A at 28 day after 15 and 30 minutes) and presented in Table 10.

4. Results and Discussion

4.1. Fresh Statute

Based on the fresh properties summarized in Table 4, the air content of specimens increased with application of fiber.

Table 5. Compressive strength

Mixture identification	7-day (MPa)	28-day (MPa)	56-day (MPa)
SW	21.5	32.0	33.0
SW0.8-15	22.0	35.6	37.4
SW0.8-25	23.0	35.8	38.0
SW1.0-15	23.5	36.8	38.5
SW1.0-25	24.0	36.9	38.6

Table 6. Tensile strength

Identification of mixed concrete	7-days (MPa)	28-days (MPa)	56-days (MPa)
SW	2.8	3.4	3.5
SW0.8-15	3.0	4.8	5.4
SW0.8-25	3.5	6.5	6.7
SW1.0-15	3.1	5.5	5.6
SW1.0-25	3.6	7.7	7.8

Table 7. Flexural strength

Mixture identification	7-day (MPa)	28-day (MPa)	56-day (MPa)
SW	2.2	4.3	4.5
SW0.8-15	2.8	5.8	6.0
SW0.8-25	3.1	7.7	7.9
SW1.0-15	3.6	5.9	6.2
SW1.0-25	4.5	7.9	8.0

Table 8. Modulus of elasticity

Mixture identification	28-day (GPa)
SW	29.0
SW0.8-15	35.4
SW0.8-25	39.5
SW1.0-15	36.5
SW1.0-25	51.3

Table 9. Water penetration depth

Mixture identification	Penetration depth of water under pressure (mm)	
	28-day	56-day
SW	16	14
SW0.8-15	17	16
SW0.8-25	19	17
SW1.0-15	18	17
SW1.0-25	19	18

Table 10. Abrasion resistance

Mixture identification	Abrasion (mm) after	
	15 min.	30 min.
SW	1.1	1.6
SW0.8-15	0.79	0.83
SW0.8-25	0.75	0.77
SW1.0-15	0.81	0.83
SW1.0-25	0.74	0.75

4.2. Hardened Properties

4.2.1. Compressive Strength

As shown in Figure 1, although at 7 days of age, CFCSF specimens did not exhibit much compressive strength compared to the control concrete, but at 28-day and 56-day, such samples showed greater compression strength than reference specimens. However, there cannot be seen any improvements with variation of fiber type and content.

4.2.2. Tensile Strength

As shown in Figure 2, using steel fibers augmented the tensile strength at age of 28 day and 56 day. An increment regarding tensile strength was nearly twice that of fibers at the same age compared to control specimens.

4.2.3. Flexural Strength

As shown in Figure 3, the application of steel fibers augmented the flexural strength of samples. An increase regarding flexural strength of CFCSF specimens at 28 day and 56 day was more than twice when compared to the reference specimen.

4.2.4. Modulus of Elasticity

As presented in Figure 4, using steel fibers raised the modulus of elasticity in mixed concrete. The modulus of elasticity of CFCSF specimens also increased with increasing fiber content.

4.2.5. Depth of Water Penetration

The results of Table 9 show that consuming steel fibers had little impact on the permeability depth under water pressure.

4.2.6. Impact and Abrasion Resistance

According to the results presented in Tables 8 and 10, the impact strength as well as the abrasion resistance of CFCSF samples was higher than the abrasion resistance of the reference samples. The increase in impact and abrasion resistance is much more prominent at older ages.

5. Developing Relationships of Data and Comparisons

To determine the relationship between existing parameters, at first, the correlation between existing parameters should be specified. The correlation coefficient is expressed for test data by:

$$MCF = Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (1)$$

where x and y: are the parameters under consideration in this study, $\bar{x}$ and $\bar{y}$: are their average values. Using Eq. (1) the correlation coefficients among different parameters are specified and reported in Table 11. Considered parameters are Tensile Strength (TS), Compressive

Strength (CS), Flexural Strength (FS), elastic modulus (ME), Water Penetration depth (WP), Impact Resistance (IR) and Abrasion Resistance at 15 and 30 min (AR15, AR30). All of these parameters are of age 28 day.

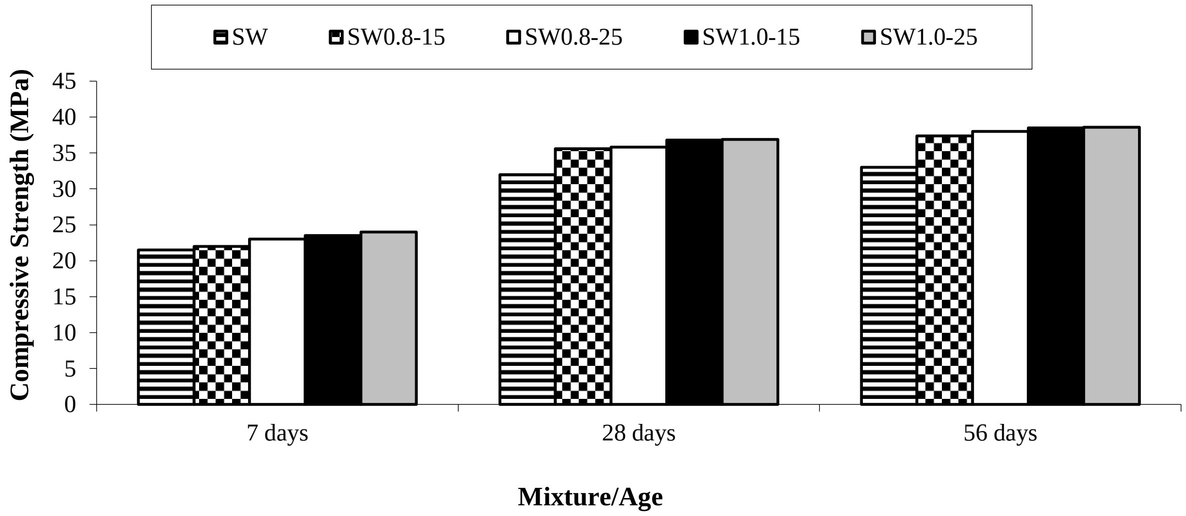


Fig. 1. Compressive strength of CFCSF mixtures compared to reference mixture

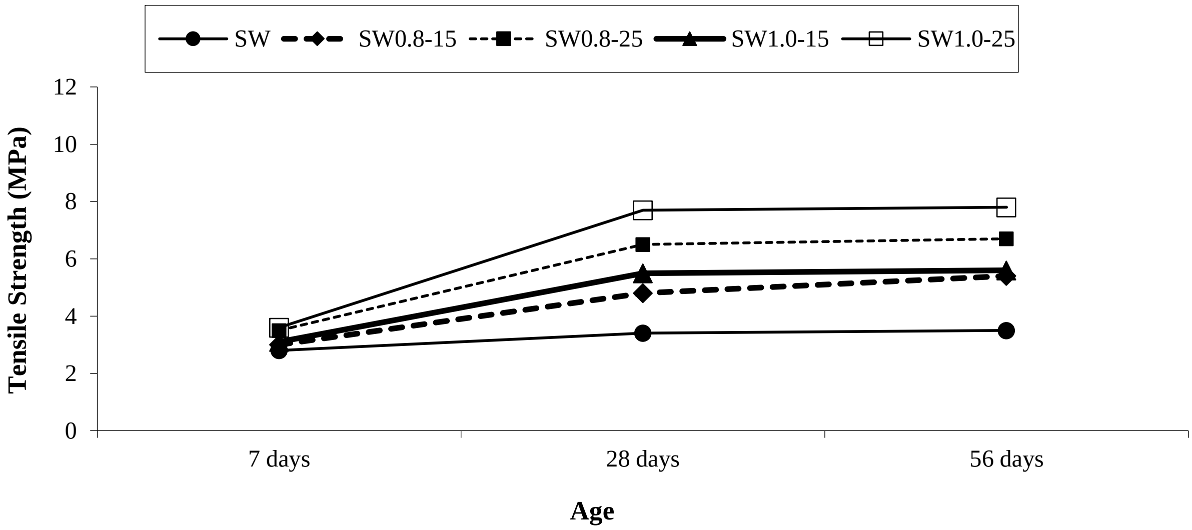


Fig. 2. Comparison of tensile strength of CFCSF mixtures with reference

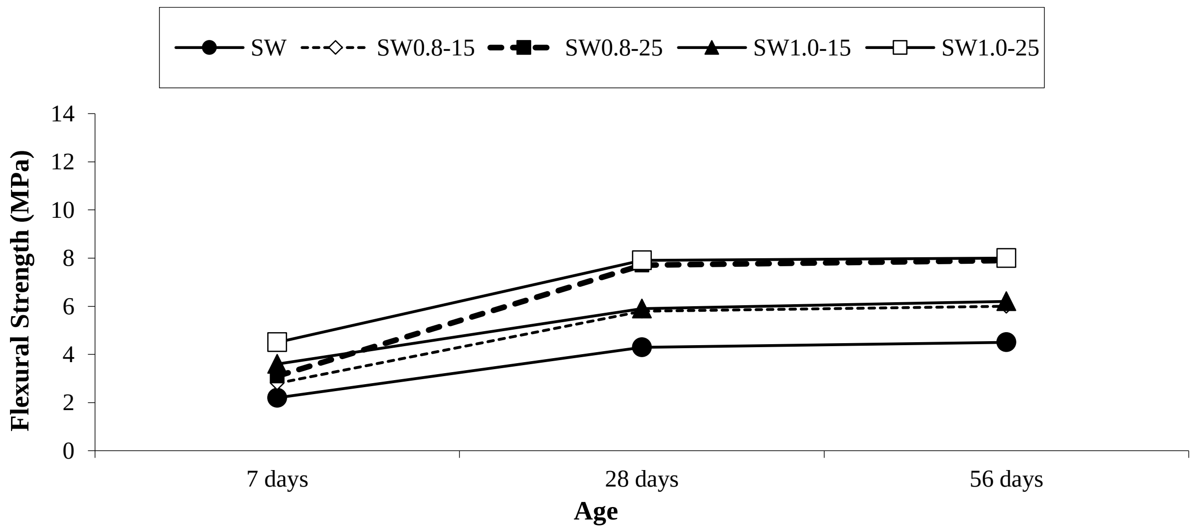


Fig. 3. Comparison of flexural strength in CFCSF mixtures with reference

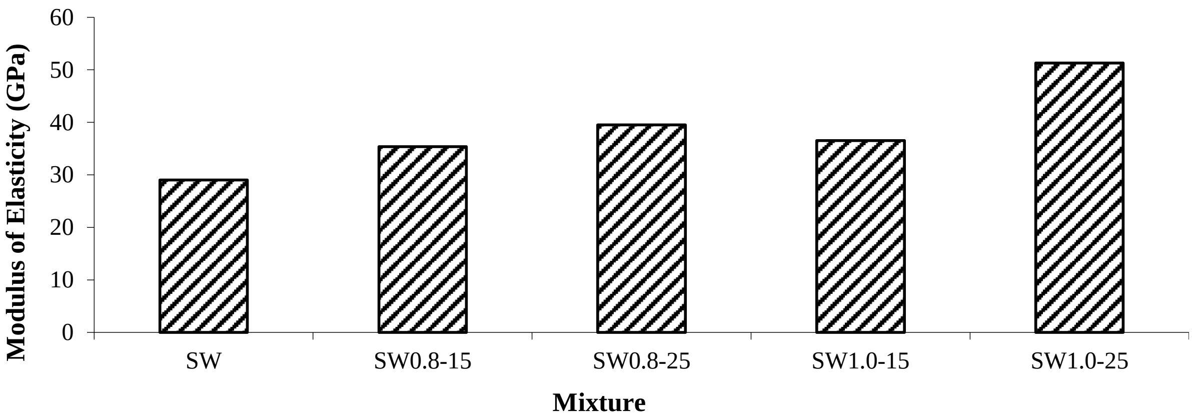


Fig. 4. Comparison of elastic modulus of CFCSF mixtures with reference

Calculated correlation parameters are various ranging from -1 to 1. Whenever the MCF becomes closer to ±1, it can be understand there is a higher correlation among actual data and outputs of model. Results reported in Table 11, reveal that it is feasible to find a relationship among results. This subject is carried out through the regression analysis by implementing the defined model as follows:

$$Y = f(b_i \times x_i) \tag{2}$$

where b_i: stands for the multipliers and x_i: indicates impressive input parameters.

In Figure 5, the relations between tensile and compressive strength, flexural strength, elastic modulus with impact resistance are demonstrated. As seen linear models were fitted to data which emphasized a direct correlation between different mechanical properties and impact resistance. As depicted, tensile strength has the most relation with impact resistance with R^2 of 0.89.

Song et al. (2004) concluded that linear regression models are accounting for most of variabilities in the impact resisting with a failure strength. However the similar trend, the gained results of current research, emphasized stronger relationship for impact resistance with tensile strength.

Also in Figure 6, relations between tensile and compressive strength, flexural strength, elastic modulus, resistance against impact and abrasion at 15 min/30 min were presented. As seen polynomial model were fitted to the experimental results with higher accuracy as depicted for abrasion resistance with modulus of elasticity.

Atis et al. (2009) compared relationships of abrasion to flexural tensile strength and abrasion to compressive strength and proposed that the relationship which is available between flexural tensile strength and abrasion is stronger than the relationship between compressive strength of the concrete and abrasion including either fibers or fly ash, or both of them. The gained results of the current study could be verified by their results; however, found relation between abrasion resistances with the modulus of elasticity proposed a better R^2 considering different utilized methods and materials.

Table 11. Correlations among results of determined parameters

MCF	CS	TS	FS	ME	IR	WP	AR15	AR30
CS	1	0.817682	0.955865	0.853068	0.874839	0.887672	-0.7384	-0.73915
TS	0.817682	1	0.79009	0.903284	0.946815	0.961204	-0.78053	-0.72952
FS	0.955865	0.79009	1	0.932148	0.845479	0.804303	-0.71933	-0.7113
ME	0.853068	0.903284	0.932148	1	0.889879	0.836315	-0.74145	-0.69982
IR	0.874839	0.946815	0.845479	0.889879	1	0.972718	-0.93163	-0.90616
WP	0.887672	0.961204	0.804303	0.836315	0.972718	0.972718	-0.93163	-0.90616
AR15	-0.7384	-0.78053	-0.71933	-0.74145	-0.93163	0.972718	-0.93163	-0.90616
AR30	-0.73915	-0.72952	-0.7113	-0.69982	-0.90616	0.972718	-0.93163	-0.90616

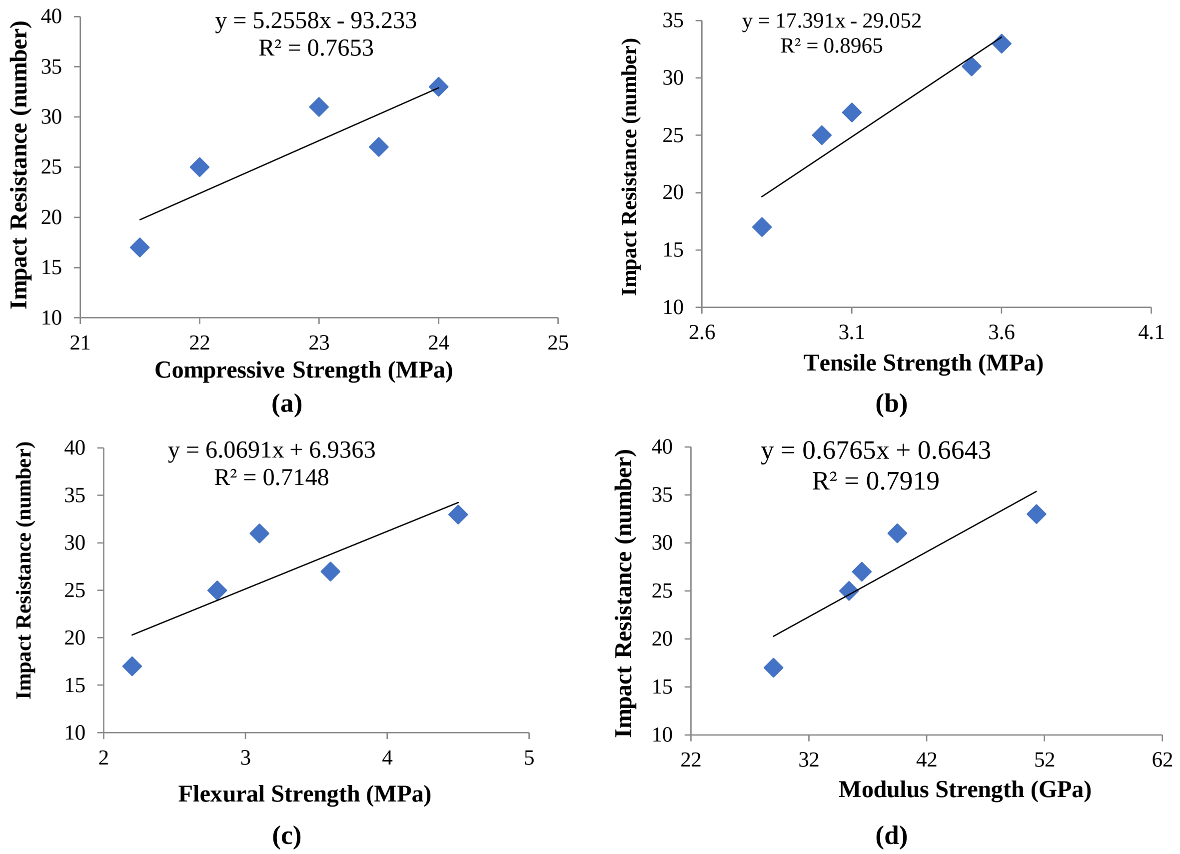
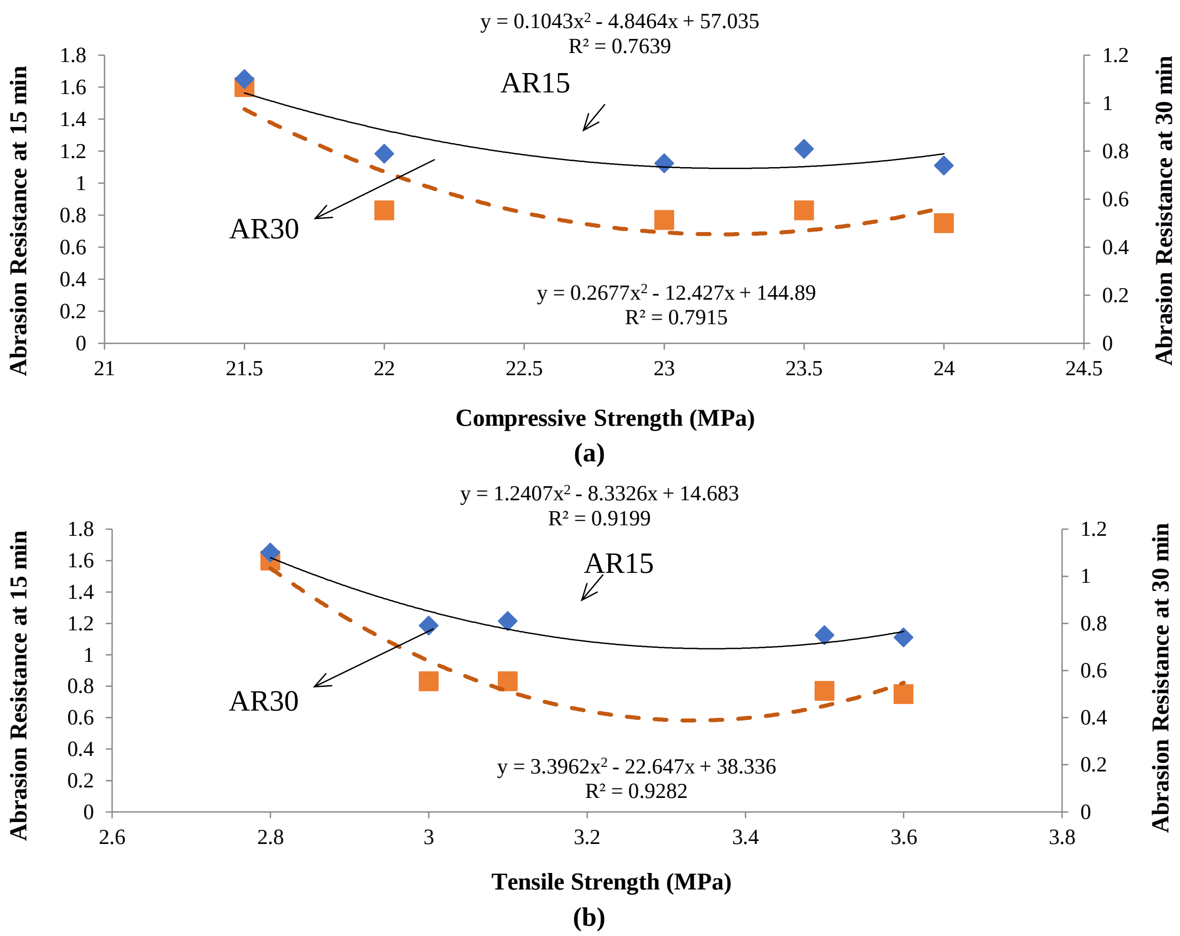
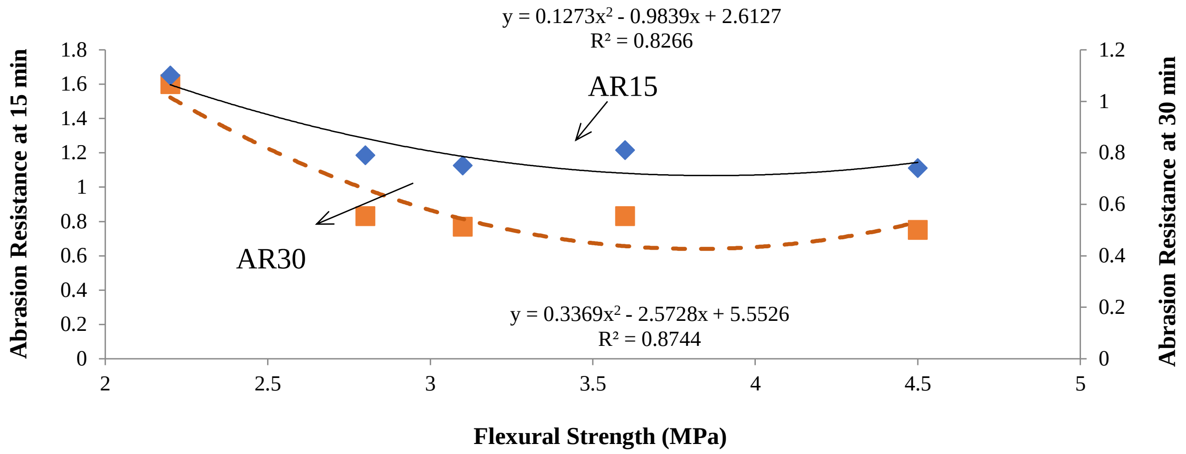
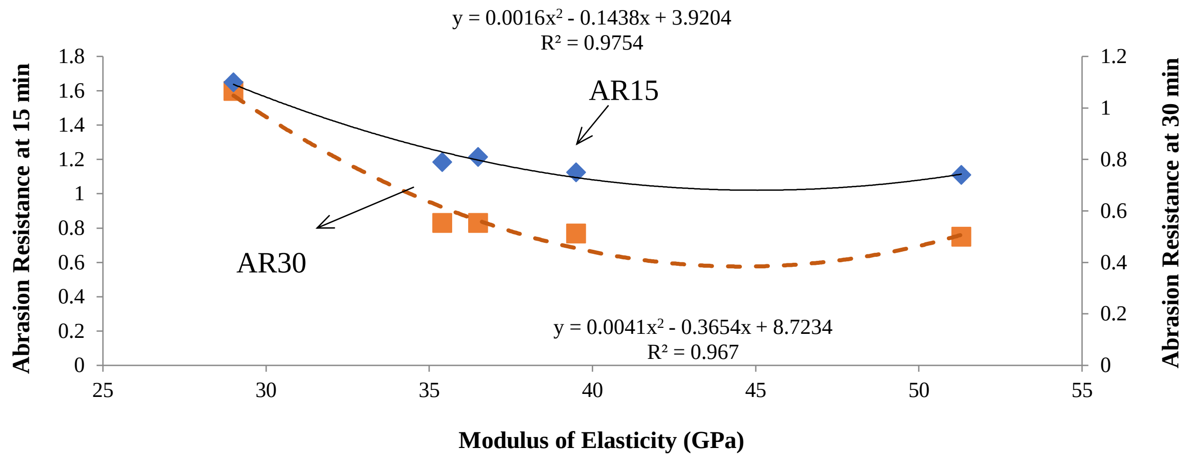


Fig. 5. Relations between: a) Compressive strength; b) Tensile strength; c) Flexural strength; and d) Elastic elasticity modulus with impact resistance





(c)



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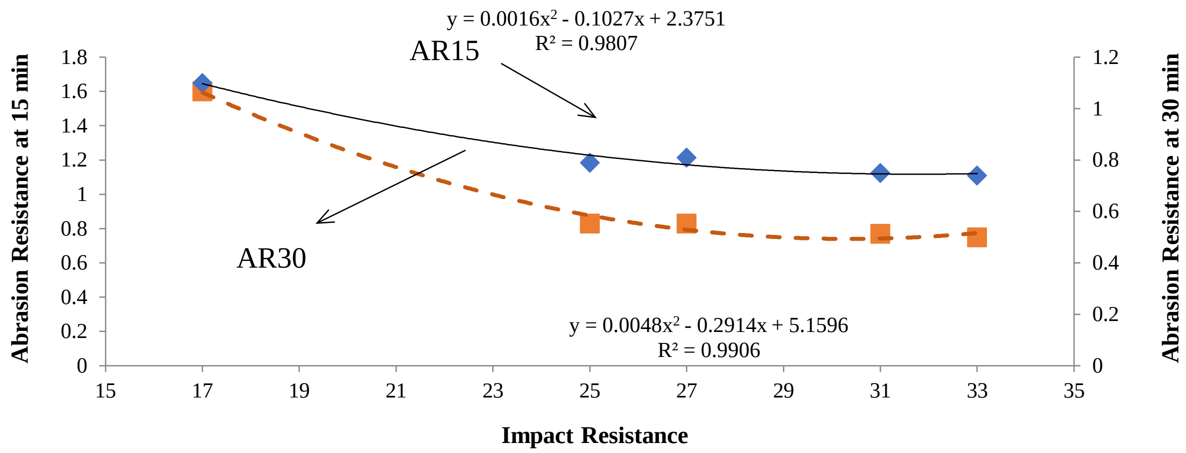

(e)

Fig. 6. Relations between compressive strength: a) Tensile strength; b) Flexural strength; c) Elasticity modulus; d) Impact resistance; and e) With abrasion resistance at 15 min/30 min

6. Conclusions

In this paper, the effects of using cold-drawn crimped-end steel fibers (CFCSF) on the durability and mechanical properties of concrete overlay was studied. Accordingly, according to the limited test results, these conclusions could be drawn as follows:

- However at the age of 7 days, steel-containing specimens did not exhibit much compressive strength in comparison with the control concrete,

but at 28 and 56 days, the compressive strength of CFCSF specimens is higher than the compressive strength of control concrete.
- The use of steel fibers has increased tensile strength at 28 and 56 days. An increase in tensile strength was about twice that of fibers at 28 and 56 days of age compared to control ones.
- Application of steel fibers has increased flexural strength. The increase in flexural strength of steel fiber samples at 28 and 56 days was more than 100% compared to the control.
- The use of steel fibers increases the elastic modulus regarding concrete. The elastic modulus of fibers containing specimens also increased with increasing fiber content.
- Using steel fibers showed a little impact on the permeability depth under water pressure.
- Impact resistance as well as abrasion resistance of fibers is higher than those of control. The increase in impact and wear resistance is much more pronounced at older ages.
- Permeability results at 56 days prove the effect of using steel fibers in hardened concrete.
- Developed models between the relation of abrasion and impact resistance to other mechanical properties, made in terms of R^2 of the linear regression and polynomial relationships, showed that stronger relations were available between impact resistance and tensile strength and abrasion resistance with modulus of elasticity.

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