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THE EFFECT OF A COMBINATION OF STEEL FIBER WASTE TYRE AND CRUMB RUBBER ON THE MECHANICAL PROPERTIES OF HIGH-STRENGTH CONCRETE

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ABSTRACT: This study examined the effect of a combination of steel fiber waste tyre (SFWT) and crumb rubber (CR) on high-strength concrete. Steel fiber and crumb rubber ranging in size from 1–2 mm were recycled from waste tires. The steel fiber waste tyre was then incorporated into high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) mixes. In this study, 10% volume of crumb rubber of maximum size passing sieve 4.75 mm was used to replace fine aggregates and steel fiber waste tyre (SFWT) dosages of 0%, 0.5%, 1.0%, 1.5%, and 2.0% by mass of concrete were added in concrete to investigate the mechanical properties of the high strength concrete. The compressive and tensile strength tests at 28 days were carried out on cylinder specimens of 150 mm diameter and 300 mm length. The results show that the addition of SFWT on HSRC and HSRFAC reduces concrete workability but increases the mechanical properties of the concrete. More SFWT are added, the higher compressive and tensile strength were obtained. The use of SFWT by 0%, 0.5%, 1.0%, 1.5%, and 2.0% on high-strength rubberized concrete (HSRC) increases the compressive strength of 2.65%, 10.55%, 20.91%, and 32.89% and the tensile strength of 5.78%, 21.97%, 32.95%, and 41.62%, respectively. The higher compressive and tensile strengths on high-strength rubberized fly ash concrete (HSRFAC) mixtures are observed at the addition of 2% SFWT with 10% content of crumb rubber. The addition of 2% SFWT improves the maximum compressive and tensile strengths up to 41.58% and 50.30%, which is 73.48 MPa and 6.46 MPa, respectively.

Keywords: High Strength Concrete, Crumb Rubber, Steel Fiber Waste Tyre, Workability, Concrete Properties

1. INTRODUCTION

The last few decades have seen an increase in vehicular density due to global development and an increase in population density. This has led to the production of huge amounts of waste tyres. Over 1.5 billion tons of waste tyre are produced annually in the world [1]. Damping used tyres on land causes many serious economic and environmental problems, as reported by previous studies [2]. Previously, scrap rubber tyres were a major environmental issue due to being discarded in landfills, buried, or burnt. An estimated over 50% of scrap tires were disposed of without proper treatment. The use of steel fiber waste tyre in concrete is a solution to resolving these problems.

Concrete structures resisting impact and earthquake loadings have been the most considerable focus in civil structural engineering design. Concrete as a construction material has been used extremely widely in high-rise buildings, bridges, and other structures due to its low cost, flexibility, durability, high strength, and resistance to fire [3]. Concrete containing steel fiber to enhance its properties is preferred in the construction of airport runway pavements, industrial flooring, bridges, military buildings and hydraulic structures where impact loading is enormous. Under impact loading, plain concrete exhibits excessive cracking and undergoes brittle failure mode with a relatively low impact energy absorption capacity. Fiber-reinforced concrete is the best choice for concrete structures resisting impact loads and limiting the initiation and propagation of plastic shrinkage cracks, which usually affect the durability of concrete structures.

The steel fiber can transfer stresses across a cracked section, which increases concrete strength and resistance to cracking and crack propagation of concrete. Steel fiber extracted from waste tyre (SFWT) can be used as an alternative steel fiber material in concrete [4]. In Indonesia, the waste tyre is one of the disposal materials with a very large amount of production, more than 50 million per year [5]. The utilization of SFWT on concrete reduces not only the environment but also the cost of concrete production, in which the cost of SFWT is approximately ten times less than manufactured steel fiber [6].

Many researchers have explored the benefits of concrete, especially for hardening [7]. For instance, Soehardjono et al. [8] report that the strength, fatigue resistance, ductility and crack ultimate, tensile strength, and fracture resistance improve. Under optimum load, the crack can be delayed to emerge in fiberized concrete compared to normal concrete, which has led to a good indication of its utilization.

Previous studies have shown that the use of recycled waste in the production of new concrete raises significant concerns about the quality of the concrete produced. To maintain the desired mechanical properties, many reinforced methods are used such as confining steel clamps to concrete [9], hemp fiber rope (HFR) [10], glass fiber chopped strand mat (FCSM) sheets [11], and hemp-fiber - reinforced polymer (HFRP) composites [12]. In addition, it is stated that the mechanical behavior of concrete reinforced with steel fibers extracted from waste tyres is comparable to that of conventional steel fiber-reinforced concrete [13].

The construction industry has been led through rapid growth due to the energy crisis and environmental consciousness. Idriss et al. [14] state that this perpetrates a large increase in waste materials such as cellulose, fly ash, silica fume, and particularly rubber from scrap tyres. The results of the laboratory work show that the replacement of fly ash with cement reduces the abrasion resistance of concrete; however, the inclusion of steel fiber improves the abrasion resistance of concrete [15]. However, the effect of the combination of the crumb rubber and steel fiber from waste tyre on HSC containing cement replacement materials such as fly ash has never been previously studied.

The current study investigates the effect of a combination of steel fiber waste tyre and crumb rubber as a partial replacement of fine aggregate on the mechanical properties of high-strength concrete and high-strength fly ash concrete.

2. RESEARCH SIGNIFICANCE

This research aims to investigate the effect of introducing the used crumb rubber (CR) and steel fiber waste tyre (SFWT) in high-strength concrete. In addition, this study reviewed the compressive and tensile strength of high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) by considering the market rate of available steel fibers of the same size and providing additional environmental benefits by reducing solid waste. The finding of this study can be used as a reference to produce strong and economical HSC as compared to ordinary HSC due to its containing steel fiber and crumb rubber materials of cheap or even cost-free from waste tyres.

3. MATERIAL

3.1 Cement

The Ordinary Portland Cement (OPC) produced by the cement factory in Padang (PT. Semen Padang), Indonesia, was used in this study.

3.2 Coarse Aggregate

The coarse aggregate was obtained from locally available aggregate with a maximum size of 10 mm as per ASTM C 128 – 07a [16]. The properties of coarse aggregate are given in Table 1.

Table 1 Properties of coarse aggregate

Property	Value
Specific Gravity	2.41
Absorption	5.93 %
Fine Modulus (FM)	3.40
Water Content	1.99 %

3.3 Fine Aggregate

Locally available fine aggregate was used in this study with a maximum size of 4.75 mm. Table 2 shows the properties of fine aggregate.

Table 2 Properties of fine aggregate

Property	Value
Specific Gravity	2.54
Absorption	3.0 %
Fine Modulus (FM)	2.85
Water Content	1.83 %

3.4 Water

Tap water was used for the mixture and curing of concrete without acids or organic substances.

3.5 Steel Fiber Waste Tyre (SFWT)

The steel fibers used in the current study were derived from cutting the cords in waste tyres, as shown in Fig.1. This steel cord was one of the products of pyrolysis processing. Fig.2 shows the steel wires were cut into small fibers (± 4 cm length) after removing them from the tyre.

Fig.1 Waste tyres

Fig.2 Steel fiber waste tyre (4 cm length)

In this study, four different fiber volumes were added to the high-strength concrete mixes at 0.5%, 1.0%, 1.5%, and 2.0% by concrete volume. The amount of SFWT in the concrete was commonly limited to about 2% by concrete volume due to a reduction in workability and difficulty in ensuring uniform dispersion [12]. The properties of steel fiber waste tyre are shown in Table 3.

Table 3 Properties of steel fiber waste tyre

Characteristic	Description
Form	Irregular, Sharp
Size	Dia. 0.5 mm and Length 40 mm
Aspect ratio	80
Density	7850 kg/m^3
Tensile Strength	500-2000 N/mm^2

3.6 Crumb Rubber (CR)

The rubber aggregates used were recycled from waste tyres through the use of mechanical grinding with sizes ranging from 1-4.75 mm (Fig.3), while specific gravity is 0.83. Table 4 shows the properties of crumb rubber. This study used a 10% volume of crumb rubber to replace fine aggregates.

Fig.3 Crumb rubber

3.7 Fly Ash

Fly ash is one of the pozzolanic materials as the cement replacement in the concrete mix, which is residue generated by the coal-burning process of the steam power plant. The fly ash used was Sijantang's power plant in Sawahlunto, Indonesia. In this study, the material of 15% fly ash was used as a cement replacement in the concrete mixture. Table 5 shows the chemical composition of fly ash.

Table 4 Properties of crumb rubber

Composition	Percentage
Carbon (C)	87.50
Oxygen (O)	9.24
Zinc (Zn)	1.77
Sulfur (S)	1.07
Silicon (Si)	0.20
Magnesium (Mg)	0.14
Aluminium (Al)	0.08

Table 5 Chemical composition of fly ash

No	Composition	Percentage
1	Silicon Dioxide (SiO_2)	51.7
2	Aluminium Trioxide (Al_2O_3)	26.47
3	Iron Trioxide (Fe_2O_3)	9.96
4	Calcium Oxide (CaO)	10.23
5	Magnesium Oxide (MgO)	0.86
6	H_2O	0.16
7	Sulfur Trioxide (SO_3)	0.32
8	Lost in annealing	0.22
9	Sodium Dioxide (Na_2O)	0.18

4. EXPERIMENTAL WORK

4.1 Mix Design

Mix design of high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) with a targeted compressive strength of 50 MPa was calculated based on ACI 211.4R-08 [17]. The water/cement ratio was maintained constant in all mixes with a value of 0.39. An optimum value of rubber content of 10% was mixed with different percentages of steel fibers (SF) by 0.5%, 1.0%, 1.5%, and 2.0% of the mass of concrete. The control mix was designated as SF 0%. Details of mixture proportion of the concrete mixtures are listed in Tables 6 and 7.

Table 6 Mix proportions of high-strength rubberized concrete (HSRC)

Material	SF 0%	SF 0.5%	SF 1.0%	SF 1.5%	SF 2.0%
Cement (kg/m^3)	555.4	555.4	555.4	555.4	555.4
Sand (kg/m^3)	581	581	581	581	581
Coarse Aggregate (kg/m^3)	1148	1148	1148	1148	1148
Water (kg/m^3)	218.6	218.6	218.6	218.6	218.6
SFWT (%)	0.0	0.5	1.0	1.5	2.0
Crumb Rubber (kg/m^3)	64.6	64.6	64.6	64.6	64.6

Table 7 Mix proportions of high-strength rubberized fly ash concrete (HSRFAC)

Material	SF 0%	SF 0.5%	SF 1.0%	SF 1.5%	SF 2.0%
Cement (kg/m^3)	472	472	472	472	472
Sand (kg/m^3)	581	581	581	581	581
Coarse Aggregate (kg/m^3)	1148	1148	1148	1148	1148
Water (kg/m^3)	218.6	218.6	218.6	218.6	218.6
SFWT (kg/m^3)	0.0	0.5	1.0	1.5	2.0
Crumb Rubber (kg/m^3)	64.6	64.6	64.6	64.6	64.6
Fly Ash (kg/m^3)	83.4	83.4	83.4	83.4	83.4

Note: SF = steel fiber

4.2 Specimen Preparation

A total of 60 cylinder specimens were prepared, consisting of 30 cylinders for compressive strength testing and 30 cylinders for tensile strength testing. Table 8 shows the number of tested specimens.

Table 8 Number of test specimens

No	SFWT (%)	HSRC Compressive	HSRC Tensile	HSRAC Compressive	HSRAC Tensile
1	0	6	6	6	6
2	0.5	6	6	6	6
3	1.0	6	6	6	6
4	1.5	6	6	6	6
5	2.0	6	6	6	6
Total		30	30	30	30

Cylindrical molds with a diameter of 150 mm and 300 mm height were used in the manufacture of test specimens for compressive and tensile strength tests. The specimens were cast with 0%, 0.5%, 1.0%, 1.5%, and 2.0% content of SFWT and CR 10% on high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC). Curing the test specimen was conducted in a water bath at the Materials and Structures Laboratory of the Department of Civil Engineering, Andalas University.

4.3 Testing of Specimens

The compressive strength test on cylindrical specimens was tested based on ASTM C 39-05 [18], and the tensile strength test was based on ASTM C 496-17 [19]. The compressive strength of the HSRC and HSRFAC at the age of 28 days were tested using the Universal Testing Machine at the Material, Soil Mechanics and Highway Laboratory, Department of Civil Engineering, Padang State University (Figs.4 and 5).

Fig.4 Compressive test on cylindrical specimen

Fig.5 Splitting tensile test on cylindrical specimen.

5. RESULTS AND DISCUSSION

5.1 The Workability of the Concrete Mixture

In this study, the workability of the concrete mixtures was measured using the slump flow test. The slump flow results of rubberized concrete mixtures with a variation of SFWT content are shown in Table 9. As seen in the table, the workability of high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) decreases as the percentage of SFWT increases. The lowest slump of all mixtures was observed at 2% SFWT content. In HSRC, the addition SFWT of 0.5%, 1%, 1.5%, and 2% reduced slump value by 49 mm, 38 mm, 31 mm, and 26 mm, respectively. For HSRFAC, the use of 0.5%, 1.0%, 1.5%, and 2.0% SFWT in high-strength rubberized fly ash concrete decreased the slump value by 56 mm, 47 mm, 40 mm, and 30 mm, respectively. The maximum slump values of 64 mm and 68 mm were observed at a rate of 0% SFWT in HSRC and HSRFAC, respectively.

Table 9 Slump value of test specimens

No	SFWT (%)	Slump Value (mm)		Percentage of Decrease (%)	
		HSRC	HSRFAC	HSRC	HSRFAC
1	0	64	68	-	-
2	0.5	49	56	23.08	17.73
3	1.0	38	47	40.56	30.53
4	1.5	31	40	51.05	41.5
5	2.0	26	30	60.14	56.12

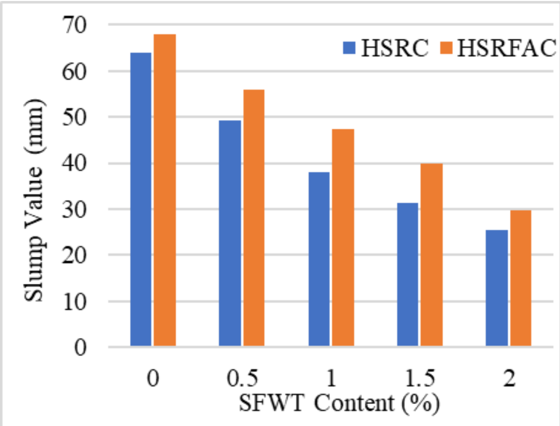

Fig.6 Slump flow of HSRC and HSRFAC with different SFWT content

The addition of high rates of SFWT affects the fluidity of crumb rubber mixtures because the SFWT prevents the flow of the cement paste. Fig.6 shows the comparison of slump flow with the variation of SFWT in HSRC and HSRFAC concrete mixtures. From the figure, it can be seen that the slumps of the HSRC and HSRFAC mixtures show a downward trend with the increased steel fiber contents. It is revealed that rubberized concrete containing SFWT has a higher slump flow in the variation of SFWT 0%. This might be due to the different surface area and water absorption capacity between steel fiber and aggregate materials.

5.2 Compressive Strength Test

The compressive strength of all mixtures was tested after 28 days of casting. The results of the compressive tests performed on high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) with different percentages of SFWT are shown in Table 10 and Fig.7. As seen in Table 10, the result of the compressive strength of the test specimens for HSRC and HSRFAC without the addition of steel fiber waste tyre (SFWT) was 50.3 MPa and 51.9 MPa, respectively. The compressive strength results of high-strength rubberized concrete (HSRC) containing SFWT content by replacing 0.5%, 1%, 1.5%, and 2% were 51.63 MPa, 55.61 MPa, 60.82 MPa, and 66.84 MPa, respectively.

Meanwhile, for high-strength rubberized fly ash concrete (HSRFAC) containing SFWT content, the compressive strength results by replacing 0.5%, 1.0%, 1.5% and 2.0% of volume with SFWT were 53.91 MPa, 57.83 MPa, 63.29 MPa and 73.48 MPa, respectively.

The highest increase in compressive strength value occurred when the SFWT was 2.0%, with an increase of 32.89% for HSRC and 41.58% for HSRFAC, while the increase in compressive strength values was at the lowest when SFWT was 0.5%, with an increase of 2.65% for HSRC and 3.88% for HSRFAC.

Table 10 Compressive strength result

No	SFWT (%)	Compressive Strength (MPa)		Percentage of Increase (%)	
		HSRC	HSRFAC	HSRC	HSRFAC
1	0	50.3	51.9	-	-
2	0.5	51.63	53.91	2.65	3.88
3	1.0	55.61	57.83	10.55	11.43
4	1.5	60.82	63.29	20.91	21.95
5	2.0	66.84	73.48	32.89	41.58

Based on Table 10, the regression equations to predict the increase in strength of HSRC and HSRFAC as function of the amount of SFWT are obtained, as expressed in Eq. (1) and (2) respectively:

$$f'c_{HSRC} = 17.4 + 3(SFWT) \quad (1)$$

$$f'c_{HSRFAC} = 15.17 + 3.22(SFWT) \quad (2)$$

where $f'c_{HSRC}$ = compressive strength of HSRC, $f'c_{HSRFAC}$ = compressive strength of HSRFAC, and SFWT = percentage of SFWT.

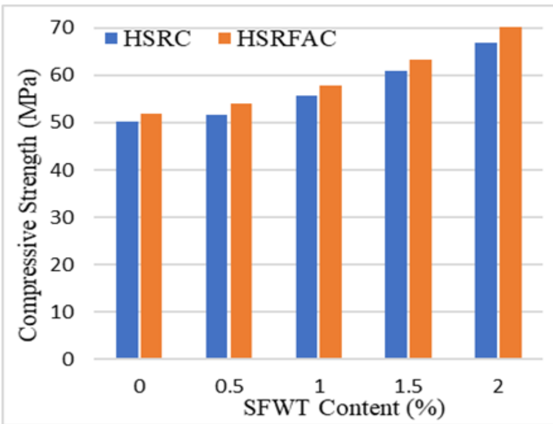

Fig.7 Comparison of compressive strength between HSRC and HSRFAC with variation SFWT content

Fig.7 shows that the compressive strength value tends to incline as the SFWT as a partial replacement of fine aggregate content increases in the high-strength rubberized concrete with and without fly ash. This indicates that the use of SFWT with a high percentage increases the compressive strength of the rubberized concrete. The fiber sizes become longer; post-yield load carrying capacity and toughness increase but under specific conditions that specimens only in the static condition. Including steel fiber in tested specimens helps further reduce the cracking number and maximum width.

Fig.8 shows the comparative results of the compressive strength test with the previous studies.

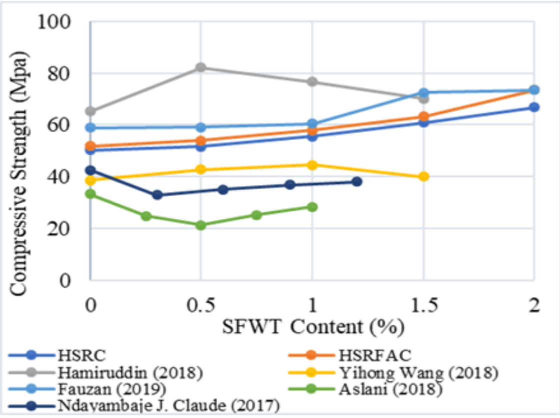

Fig.8 The comparison of compressive strength with different SFWT content

Based on Fig.8, the compressive strength of the results of this study has increased with the increase in SFWT in the mixture in concrete. According to Fauzan et al. [21], the compressive strength of concrete in additional SFWT with and without fly ash increases because the SFWT content in the concrete mixture increases as well. However, in previous studies [22-24], it was found that the compressive strength decreased with the initial addition of SFWT to the concrete mixture. Still, another previous study [25] stated that the compressive strength of concrete increased as the SFWT in the concrete mixture increased, although the compressive strength of concrete decreased when the SFWT content was 1.5%.

5.3 Tensile Strength Test

The results of the splitting tensile tests performed on high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC) mixtures with different percentages of steel fiber waste tyre (SFWT) are shown in Table 11 and Fig. 9.

As seen in Table 11, the splitting tensile strength increases but at a lower value compared to compressive strength. At 0.5%, 1.0%, 1.5%, and 2% of SFWT as partial replacement fine aggregates, the increase in split tensile strength for HSRC and HSRFAC are 5.78%; 21.97%; 32.95%; 41.62% and 10.18%; 19.76%; 37.13%; 50.30% at 28 days respectively. The lowest tensile strength value is 4.1 MPa and 4.3 MPa without the addition of steel fiber, which slightly decreases with the addition of 5% SFWT in the concrete mixture. The replacement of 1.0%, 1.5%, and 2.0% aggregates with steel fiber results in the tensile strength of 5.0 MPa; 5.45 MPa; 5.81 MPa for HSRC and 5.15 MPa; 5.9 MPa; 6.46 MPa for HSRFAC, respectively.

Table 11 Tensile strength of HSRC and HSRFAC

No	SFWT (%)	Tensile Strength (MPa)		Percentage of Increase (%)	
		HSRC	HSRFAC	HSRC	HSRFAC
1	0	4.1	4.3	-	-
2	0.5	4.34	4.74	5.78	10.18
3	1.0	5.0	5.15	21.97	19.76
4	1.5	5.45	5.9	32.95	37.13
5	2.0	5.81	6.46	41.62	50.3

Fig. 9 shows that the tensile strength of HSRC and HSRFAC increases by increasing the steel fiber waste tyre (SFWT) content. This indicates that the higher SFWT content results in an increase in the tensile strength of the high-strength rubberized concrete (HSRC) and high-strength rubberized fly ash concrete (HSRFAC).

From Table 11, the regression equations to predict the increase in tensile strength of HSRC and HSRFAC as function of the amount of SFWT can be expressed in Eq. (3) and (4) respectively:

$$f't_{HSRC} = 1.7 + 0.4(SFWT) \quad (3)$$

$$f't_{HSRFAC} = 1.64 + 0.43(SFWT) \quad (4)$$

where $f't_{HSRC}$ = tensile strength of HSRC, $f't_{HSRFAC}$ = tensile strength of HSRFAC, and SFWT = percentage of SFWT.

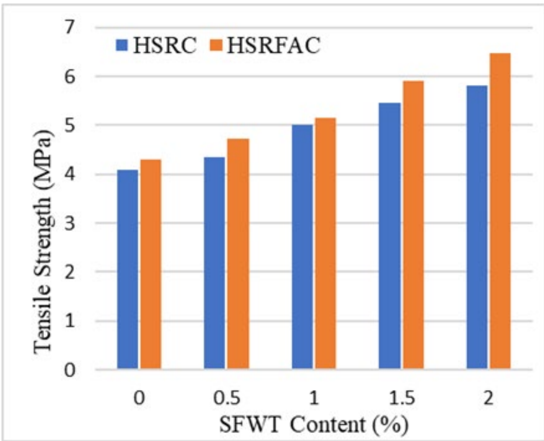

Fig.9 Tensile strength with variation SFWT content

The tensile splitting strength increases as the increase of fiber content from 0% to 2% on HSRC and HSRFAC mixtures. The increase in the tensile strength might be due to the bridging action of the SFWT, which results in a stronger mechanical interlocking force in the concrete [20].

From Fig. 9, it is also seen that high-strength rubberized fly ash concrete (HSRFAC) mixes show better results than high-strength rubberized concrete (HSRC). The reason for this is because of the high pozzolanic nature of the fly ash and its void-filling ability, lead to improve the tensile strength of the concrete.

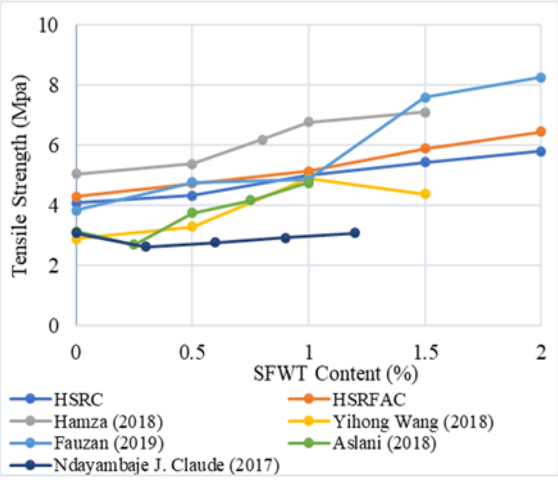

Fig.10 The comparison of tensile strength results

Fig.10 shows the comparative results of the tensile strength test with the previous studies. It can be seen from the figure that the tensile strength in this study experienced a significant increase with the increase of SFWT in concrete. In the previous study [21], the tensile strength of concrete addition of SFWT with and without fly ash experienced an increase that resembled an increase in tensile strength in this study. Previous studies on concrete with a mixture of crumb rubber and SFWT [23-26] show that the tensile strength of concrete increases as the increase of SFWT content in the concrete mixture, although a decrease occurs at the beginning of the addition of SFWT [23,24] and at the end of the addition of SFWT [25].

6. CONCLUSION

Based on the experimental investigation, the following conclusions were drawn:

1. The addition of SFWT of 0.5%, 1%, 1.5%, and 2% in high-strength rubberized concrete (HSRC) reduces slump flow diameter by 49 mm, 38 mm, 31 mm, and 26 mm, respectively. Meanwhile, high-strength rubberized fly ash concrete (HSRFAC) reduces slump flow diameter by 56 mm, 47 mm, 40 mm, and 30 mm.
2. In HSRC and HSRFAC, when the steel fiber waste tyre content varies from 0.5% to 2%, the compressive strength increases by 2-33% and 4-42%, respectively. The maximum compressive strength in HSRC and HSRFAC containing SFWT occurs in the addition of 2.0% steel fiber, that is, 66.84 MPa and 73.48 MPa, which increases by 32.89% and 41.58%, respectively.
3. In the splitting tensile test, the addition of 0.5% to 2% SFWT in HSRC and HSRFAC reaches the maximum tensile strength of 5.81 MPa and 6.46 MPa, respectively, in which the increase of the tensile strength is around 41.62% and 50.30%, respectively, in comparison with the mixtures without SFWT.

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