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Investigating the Effect of Steel Wire and Carbon Black from Worn Out Tyre on the Strength of Concrete

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ABSTRACT

Technology in concrete is rapidly developing to improve the quality and properties of concrete. One of the many recycled materials is worn-out tyres. Currently, the use of tires is very widespread considering the use of vehicles that increase from time to time. Piles of discarded tires can cause a lot of damage to the environment. So, by using steel wire waste (SWW) as new fiber reinforcement in concrete and with the combination with carbon black (CB), it is hoped that, by doing this, not only it could improve the quality of concrete, but also preserves the environment. Therefore, the objective of this research was, to identify the properties of fresh concrete with the addition of SWW and CB, and also to investigate the physical and mechanical properties of hardened concrete, incorporating of SWW as additional fiber reinforcement and CB. For fresh concrete, workability using a slump test was conducted. Several tests were carried out on the properties of hardened concrete. Among them were compressive strength, flexural strength, splitting tensile strength, and water absorption. The physical appearance of the concrete has also been examined and recorded. There are four batches of concrete which consist of one control batch and three batches of concrete with various weights of SWW which are in the portion of 300 g, 600 g, and 900 g, and the weight of CB is maintained at 300 g for all batches. For workability, all concrete batches with the addition of SWW and CB show acceptable workability. For the case of the density of fresh concrete, samples containing 900 g addition of SWW have the highest density which was 2520 kg/m^3, as expected. Results for water absorption show that the lowest value is contributed by the control sample which was 7.6%. For compressive and flexural strength, 300 g addition of SWW has the highest value which was 28.52 MPa for compressive strength and 7.52 MPa for flexural strength. Lastly, for splitting tensile strength, the highest value was also obtained when 300 g addition of SW was added which was 5.4 MPa. To conclude, SWW and CB can be added to concrete to obtain comparable strength of concrete. However, some modifications could be made to both recycle materials to improve concrete performance.

Keywords: *Concrete, steel wire waste, carbon black, compressive strength, recycling*

1. INTRODUCTION

Tires are made from a variety of materials, including natural rubber, synthetic rubber, steel, nylon, silica, and others, and are used as major components of vehicles. Due to its moderate lifespan, which varies from four to ten years, the frequency of tires being changed will increase especially if it is being used roughly especially for trucks and heavy-duty vehicles. The components of tires consist of mainly rubber, carbon black, steel fibers, and textiles fabric or carbon fiber which makes it difficult to be composed naturally. It is estimated that more than 3 million or about 60 tons of used tires are produced every year but more than 70% of them are not used and placed in storage which will take out many spaces. A multitude of health problems, including an escalated danger of fire ignition and a breeding ground of pests like rodents and mosquitoes, can arise from the improper disposal of worn-out tires. The smoke generated from the burning of tires contains many harmful chemicals especially heavy metals which are toxic to human and animal health. Many locations where the tires are dumped become useless because of the abundance of worn-out tires piling up which resulted in the scarcity of the land [1]. As they slowly start to decompose, they release harmful chemicals into the atmosphere. Every year, 32 million tires are buried and that does not account for the thousands who are illegally dumped.

The worn-out tires can be recycled for new beneficial materials, such as material in modified asphalt mixture or being utilized in concrete, among many other things [2]. The primary goal of this research is to ascertain whether steel wire waste (SWW) from worn-out tires can increase concrete strength or the opposite with the combination of carbon black (CB) from the same source. To improve the engineering qualities of concrete, the use of steel materials as an additional or replacement material is becoming more and more popular choice amongst researchers. The use of SWW in concrete can provide additional reinforcement and become a strengthening materials in concrete structure [3]. Typically, the steel fibers used in concrete are dispersed throughout standard concrete during mixing which will create a concrete mixture called steel fiber reinforced concrete (SFRC). SFRC is a promising potential advanced building material that includes randomly distributed steel fibers of various shapes and geometries into the cement matrix to increase the durability and strength of concrete [4]. Commercial steel fiber is typically classified into three main shapes based on manufacturing forms: straight form, hooked ends form, twisted form, or corrugated form.

The strength of SFRC is critically determined by the number of fibers added to it. Preliminary attempts have been made to incorporate the SWW directly into the concrete mixture. However, the mixture has a major segregation problem with the entanglement of the SWW and the hardening process of concrete and mortar becoming difficult and consequently affecting the strength of concrete [5]. Significant reductions in concrete workability, are likely to occur when a higher percentage of SWW is used. The use of recently designed high-range superplasticizers, which strengthen the workability of SFRC as well as spreading the mix's elastic properties, could help to reduce this issue.

Meanwhile, CB is a fine powder composed mostly of carbon particles that are produced by incomplete combustion or thermal decomposition of hydrocarbons. Carbon black is commonly used as a reinforcing filler in rubber products such as tires, as well as in plastics, paints, inks, and various other applications where its properties, including its ability to impart strength, durability, and color, are advantageous.

This research is focusing on the use of SWW and CB, which both are, a by-product of a tire recycling process, in concrete mixture and its effect on the strength of the concrete. The properties of concrete mixtures containing SWW and CB were investigated in their fresh and hardened state. Previous studies mostly focused on utilizing the CB in nano-size and typically in self-monitoring concrete [6][7]. Studies on the combination of SWW and CB in concrete are very limited and it is quite difficult to find the discussion regarding these combinations on the performance of concrete.

2. MATERIALS AND METHODS

2.1. Raw Materials Preparation and Testing

The normal SFRC consists of SWW with cement, sand, coarse aggregate, and water. Prior to the SWW being used in the mixture, it was necessary to sort the steel wire from other materials it was mixed with, such as rubber, steel, nylon, silica (derived from sand), carbon fiber or textile, carbon black, and possibly more additional substances. Lengths exceeding 100 mm must be avoided to prevent aggregation or clumping of SWW, which for this study the longest SWW is 60 mm. Fig. 1 shows the condition of various substances contained in the worn tire samples, the rubber crumb, CB, and the SWW waste with its two major sizes. It can be noted that a major component of worn tires is the crumb rubber which comes in bigger size. Table 1 indicates the concrete mix proportion. Four concrete batches were prepared which are one control batch and three batches with different weights of SWW (300 g, 600 g, and 900 g), and CB content is fixed at 300 g. Rather than replacing several percentages of coarse aggregate with the SWW, this research emphasizes the addition of SWW in the mixtures, to increase the strength. The free-water ratio of 0.5 was controlled during handling the mixture to achieve the targeted concrete strength of this research. Ordinary Portland Cement that complied with Malaysian Standard, (2009) was used as binder material in casting the concrete specimens. Natural sand obtained from a local riverbed is used as the fine aggregate. Clean water that was free from any impurities was used in the process of casting the control samples and samples containing SWW and CB. CB is shown in Fig. 2 with the size of CB is 5mm which is quite the same with sand. For the SWW, the diameter of the SWW selected is 0.20 mm and the length is approximately 60 ±10 mm as shown in Fig. 3. No further adjustment to the SWW has been made prior to the addition in the concrete mixtures.

Both sand and coarse aggregate were sieved before they were used in the concrete mixture following the standard method [8]. The purpose of sieving was to remove any particles that were excessively large or small, ensuring that the materials used in the concrete were within the desired size range. This sieving process helps to improve the overall quality and workability of the concrete mix. The manual mixing process is involved in this research, where the materials are combined and mixed thoroughly until a uniform consistency is achieved.

Fig. 1 – The SWW (a) original forms collected on site (b) rubber residue (c) steel wire with 0.2 mm diameter and (d) steel wire with a diameter 0.95 mm

Fig. 2 – Carbon black

Table 1 – Mix-proportion of raw materials

Testing	Cement (kg)	Water (kg)	Sand (kg)	Granite (kg)	SWW (kg)
Compressive strength	4.1	1.8	7.0	9.1	0.3
Flexural Strength	6.8	2.8	11.5	15.3	0.6
Splitting Tensile Strength	7.2	3.0	12.2	16.2	0.9

Fig. 3 – The selected SWW in diameter of 0.20 mm

2.2. Workability of Fresh Concrete

To establish how easily a concrete mixture may be moved, placed, and handled during construction, it is essential to evaluate its workability. The workability of concrete was tested by slump test. The effect of different amounts of additional SWW and CB in a fresh concrete state can be determined by measuring the depth of collapse. The test method was based on the standard test method [9]. Fig. 4 shows one of the concrete mixtures containing the SWW and CB. The SWW is dispersed in the mixture and some of them were tangled with one another. However, the CB cannot be seen clearly because it has been mixed well in the mixture.

Fig. 4 – A concrete mixture containing SWW

2.3. Testing on Hardened Concrete

The density of concrete is an important property that provides information about its mass per unit volume. It is influenced by various factors, including the proportions of the ingredients used in the concrete mixture. The density of the concrete samples was measured after 28 days of curing. This allows for the evaluation of how the addition of SWW and CB affects the density of the concrete. The concrete specimens were cast using a mold with dimensions of 100 x 100 x 100 mm where the average value from 3 sample cubes was used for each addition of 0 g, 300 g, 600 g, and 900 g of SWW in each mixture, accordingly. The concrete specimens were carefully removed from the molds after the specified curing times. To get rid of any loose debris or particles that might skew the density measurements, the outer surfaces were cleaned. By calculating the concrete samples' mass and volume, the density of the samples was calculated. The method to calculate density was following the standard method stipulated in [10]. For the water absorption test, the same mold size of 100 x 100 x 100 mm was selected for this experiment. Water absorption value for concrete can be determined using a method as described in ASTM C642 (2015). The hardened concrete specimens were immersed in a water bath and left for at least 24 hours. Then, it was removed from the tank and drained out and its surface was dried using a towel or cloth. A mass of saturated surface dried specimens was recorded. After that, these specimens were placed in the laboratory oven for 24 hours at a working temperature of 100 ± 5 °C. The weight of dry specimens was immediately measured.

Concrete's compressive strength, which indicates the material's capacity to withstand compressive forces and resist deformation, was a crucial characteristic. A compressive strength test was performed after the samples had been cured for 7 and 28 days, respectively. The test at 7 days is required to identify whether the early strength of the concrete samples has been achieved or vice versa and to understand if the combination of SWW and CB has an influence on the achievement of the early strength of concrete samples. The mold used for the determination of compressive strength measures 100 x 100 x 100 mm. For each addition of 0 g, 300 g, 600 g, and 900 g of steel wire waste in cement for 7 and 28 days of curing, 3 cubes were used. The test method used was following the guidelines in [11].

The flexural test was carried out on 12 rectangular specimens with dimensions of 100 mm x 100 mm x 500 mm and tested based on the standard method [12]. Flexural testing was performed using a universal three-point loading machine with a loading capacity of 1000 KN. The method of testing is shown in Fig. 5. During the experiment, the loading and mid-point displacement values were automatically recorded on a computer.

For the splitting tensile strength test, the size of the mold used in this test was 150 mm in diameter and 300 mm in height. 3 cylindrical had been used for each addition of 0 g, 300 g, 600 g, and 900 g of SWW waste in cement for 28 days of curing. So, the total beam mold used was 12. In this test, the method in ASTM C496 was adopted. Concrete was poured into the molds being compacted. After 24 hours, the molds were removed, and the cylindrical beams were cured in a curing tank. Splitting tensile test was performed after the samples had been cured for 28 days. The testing of splitting tensile concrete containing SWW waste was conducted using a universal testing machine (UTM).

Fig. 5 – Flexural testing process

3. RESULTS AND DISCUSSIONS

3.1. Properties of Main Raw Materials

In Fig. 6 the grain size distribution and grading curve of sand used in concrete casting are shown and plotted. In terms of the smoothness of the grading curve, the sand did not contain large deficiencies or excesses of any size, indicating that it has a relative smoothness based on graph observation. Nonetheless, the fineness modulus calculated was 2.9, which was within the range between 2.3 and 3.1. Therefore, the raw sand was considered medium sand in size.

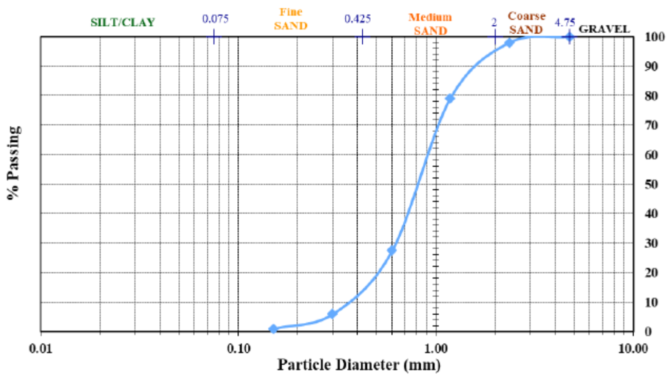

Fig. 6 – Particle Size Distribution for Fine Aggregate

Sand properties have a huge effect on the performance of both fresh and hardened concrete. Gradation or particle size distribution of sand affects the properties of concrete like density, voids content, workability, and strength [13]. If the fine aggregate is too coarse, bleeding, segregation, and harshness will occur, but if it is too fine, water demand will increase. For raw sand that passes through the 0.60 mm, the percentage calculated was approximately 30%. This value was applied in the design mix calculation.

The coarse aggregate used for the preparation of the concrete samples was crushed stone with a maximum size of 20 mm. The grain size distribution of gravel is done by sieve analysis and the grading curve of gravel is shown in Fig. 7. In this study, crushed stone with sizes less than 20 mm was used as coarse aggregate.

The mechanical properties of SWW after conducting tensile testing are shown in Table 2. Tensile strength, yield elongation, break elongation, modulus of elasticity, and yield stress were all determined, and it can be noted that the tensile strength of samples at each load imposed is proportioned to the yield stress of the SWW. To ensure an accurate test, the proper gripping method should be used to avoid damaging the SWW. The tensile test results will be negatively affected if the SWW is damaged.

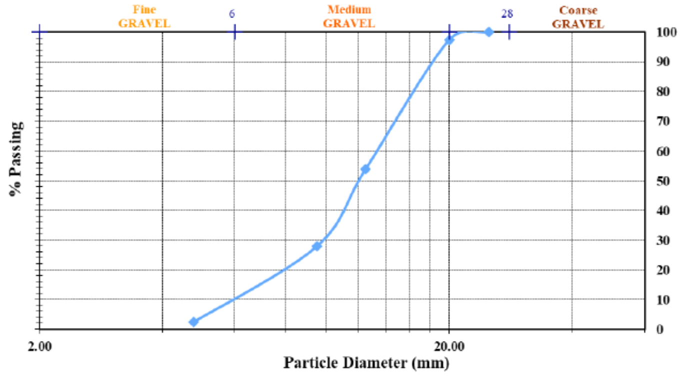

Fig. 7 – Particle Size Distribution for Coarse Aggregate

Table 2 – Properties of SWW

Maximum Load (kN)	Tensile Strength (MPa)	Yield Elongation (%)	Modulus of Elasticity (MPa)	Yield Stress (MPa)
0.01	213	3.8	4968	141
0.02	558	3.0	40141	518
0.05	1565	4.2	111397	1402

Table 3 describes the properties of CB used for this study. It can be noted that CB has the lowest density compared with OPC, which later affected the overall density of concrete because of uneven dispersion in concrete.

Table 3 – Density and specific gravity of main raw materials

Property	Coarse aggregate	Fine aggregate	OPC	CB
Density (kg/m^3)	3000	2000	1000	400
Specific gravity	2.64	2.27	0.33	0.32

3.2. Fresh Properties of Concrete

Fig. 8 shows the result of the slump test. The slump value for the control sample which has 0 g addition of SWW and 0 g CB was the highest which was 75 mm. It also appears that the height of the slump was decreased when the addition of SWW was increased in the mixture. When 300 g of SWW was added, the height of the slump was decreased to 67 mm. Then it was decreased to 65 mm when 600 g of SWW was added and 55 mm when 900 g SWW was added. The result shows that the addition of SWW and CB will affect the workability. It shows that the increased of addition of SWW decreased the workability of fresh concrete. All the fresh concrete from 0 g to 900 g can be classified as having a medium degree of workability since it is still within the acceptable range of 75±25 mm. The distribution of SWW and CB also influenced the slump value.

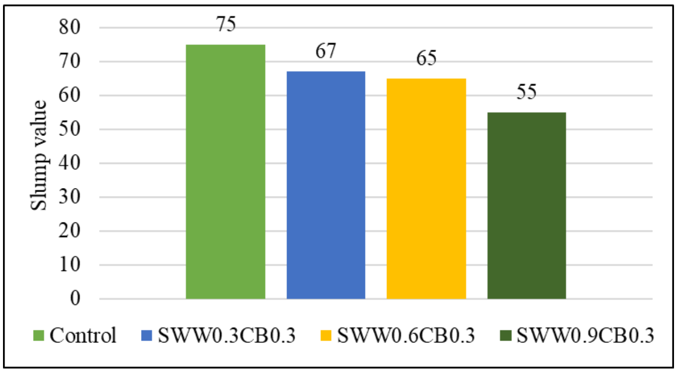

Fig. 8 – Slump Value for all concrete mixtures

3.3. Physical and Mechanical Properties of Concrete

The weight of the structure can be estimated from the concrete's density, which also provides information about the material's characteristics. The strength of concrete is generally increased by increasing its density. The effect of the addition of SWW on the density of concrete is shown in Fig. 9. Concrete samples that contain 900 g of SWW and 300 g CB has the highest density which was 2484 kg/m^3. The lowest density was 2400 kg/m^3 which is attributed to the control sample. While addition of 300 g and 600 g SWW have densities of 2458 kg/m^3 and 2466 kg/m^3 which were slightly higher than the control sample. Based on the results, SWW increased the overall density of concrete when it was used as additional reinforcement in concrete. This was because, when SWW was incorporated into the concrete, it added more mass per unit volume, resulting in an increase in the overall density of the mixture. The contribution of CB is not significant because only 300 g was added for all samples. In addition, based on raw materials results, CB its density is only 400 kg/m3 with a specific gravity of 0.32. Thus, it does not really affect the overall concrete density.

From the results, the density of concrete increased by 2.4 % from the control sample when 300 g of SWW was added which is the SWW0.3CB0.3 samples. This trend is consistent with SWW0.6CB0.3 samples and SWW0.9CB0.3. The higher the addition of SWW, the higher the density of concrete. So, we can say that SWW can improve the overall density of concrete when it is used as reinforcement in concrete. SWW causes gaps and spaces in the surrounding concrete matrix, which are subsequently filled with more concrete substance [14]. The overall density of the concrete mixture rises because of this filling effect.

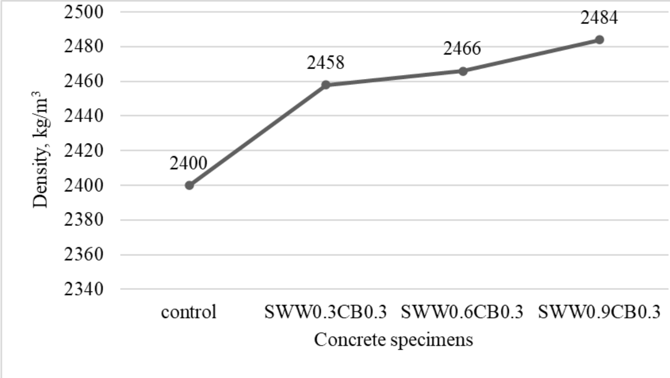

Fig. 9 – Density for all concrete mixtures

In terms of physical appearance, it can be seen clearly from Fig. 10, that the concrete samples have turned to black color due to the addition of CB. For aesthetic purposes, this CB can be considered to be used in the future.

Fig. 10 – Physical appearance of concrete with SWW and CB addition

Water absorption is primarily to investigate the transport mechanism for water in the tiny pores in concrete due to surface interactions between the water and the pore wall. The influence of the addition of SWW and CB on the water absorption of concrete is shown in Fig. 11. The control sample had the highest average water absorption. As the amount of SWW increases, the water absorption is increased. The average water absorption for SWW0.3CB0.3 specimen was 7.7 %, which increased to 8.1 % for SWW0.6CB0.3 and further increased to 11.9 % for SWW0.9CB0.3. Higher amounts of SWW resulted in higher water absorption. The presence of SWW relatively forbids achieving better compaction during the mixing and placing of the concrete, where better compaction can lead to fewer voids and air pockets [15] because of the entanglement between the SWW. However, the existing CB in the concrete is less prone to absorb water because of its nature which is hydrophobic, meaning it repels water. The surface of carbon black particles is composed primarily of carbon atoms, which do not have a strong affinity for water molecules. This hydrophobic nature is one of the reasons why carbon black is often used as a reinforcing filler in rubber products, as it helps to improve the water resistance of the rubber as in tire products. However, since the amount of added CB is not very large, it does not affect the water absorption significantly. Additionally, the presence of SWW may affect the pathways in the concrete. Microscopically small channels called pathways can allow water to be absorbed into the concrete. Moreover, SWW can also act as a barrier, obstructing the pathways and reducing the capacity for overall water absorption.

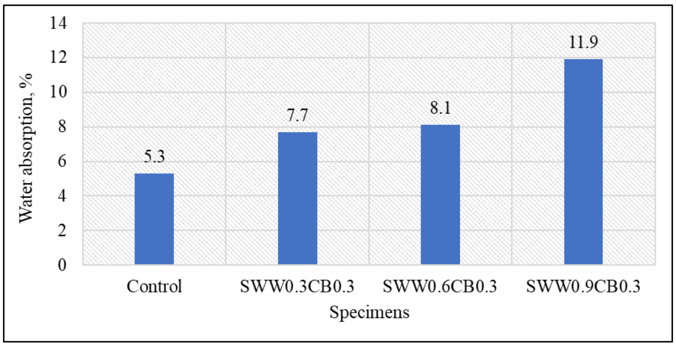

Fig. 11 – Water absorption for all concrete specimens

The addition of SWW to concrete samples had varying effects on compressive strength. As shown in Fig.11, the control sample had a strength of 25.5 MPa. Adding 300 g of SWW increased the strength to 30.5 MPa, while 600 g and 900 g additions resulted in strengths of 24.7 MPa and 19.2 MPa, respectively. According to the specified requirements for grade C25 concrete, the expected compressive strength at 28 days was 25 MPa. The highest compressive strength achieved was for SWW0.3CB0.3 with 30.5 MPa, exceeding the required strength of 25 MPa by 22 %. However, the strength of SWW0.6CB0.3 is slightly decreased at only 2 % which gives the strength of 24.5 MPa. A similar trend was also achieved for 900 g additions where the strength was remarkably decreased by 23 % compared to the targeted strength value.

Concrete, when reinforced with SWW, experiences an increase in compressive strength due to the added reinforcement. However, with the addition of CB, it affected the strength of the samples. When investigated, it was found that due to the lower density of CB compared with SWW, CB has a tendency to float on the surface and disturb the overall matrix of concrete. Therefore, even though it was added to the concrete, it did not contribute to the increase in strength. Some modification for CB is required to fully explore the potential use of CB in concrete. From Fig. 12, it can be concluded that, if the amount of SWW exceeded the optimal ratio, the additional reinforcement became excessive, leading to a decrease in compressive strength. When this happens, it may be difficult to achieve uniform dispersion and strong bonding throughout the concrete [16]. This can result in stress concentrations and weak spots, ultimately leading to a decrease in compressive strength. It is evident that the SWW in all mixtures are prone to attach with each other and are difficult to separate.

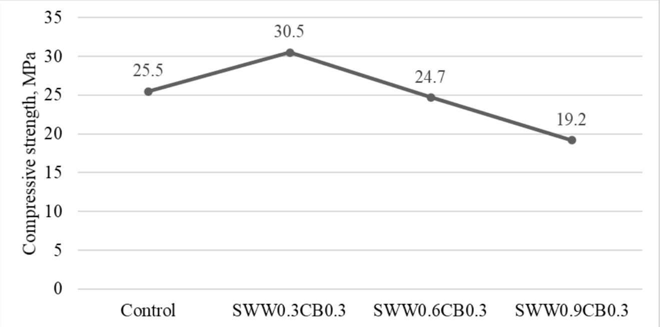

Fig. 12 – Compressive strength for all concrete mixtures

A similar trend can be evident for the flexural strength of concrete, where the addition of SWW had a significant effect on the flexural strength of concrete samples as shown in Fig 13. The control sample had a flexural strength of 3.911 MPa. For sample SWW0.3CB0.3, the flexural strength increased significantly to 6.887 MPa. However, for sample SWW0.6CB0.3, the strength decreased to 6.702 MPa and then decreased again to 6.688 MPa for SWW0.9CB0.3. The highest flexural strength achieved was well within the expected range of 2.5-5.1 MPa (10 - 20 % of compressive strength). Similarly, the flexural strengths with 600 g and 900 g of SWW additions increased compared to the required value. After 28 days of curing, the flexural strength for all samples achieved the targeted strength. This exemplifies the positive consequences of adding SWW to concrete. The findings clearly suggest that the addition of SWW has a beneficial impact on the long-term compressive strength development of the concrete as a reinforcement to the concrete. However, to ensure the full capacity of SWW in concrete is utilized, a better mixing technique can be considered to avoid self-tangling between all SWW.

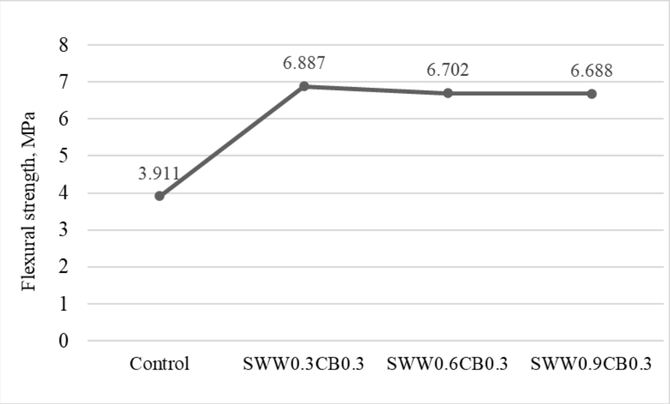

Fig. 13 – Flexural strength for all concrete mixtures

The decreasing trend may occur due to improper distribution of SWW in concrete as in agreement with the discussion from [5]. To achieve balanced reinforcement and efficient load distribution, the SWW must be distributed properly throughout the concrete. If the wire is not evenly distributed or properly positioned throughout the concrete, it may produce isolated regions of weak reinforcement, which may lower the material's overall flexural strength. As for CB, it also does not make a major contribution to the flexural strength of concrete samples. This may maybe because of the smaller amount of CB used in all samples.

For the splitting tensile strength of concrete, a similar trend can be observed for all cases as shown in Fig.13. Control sample shows the second lowest splitting tensile strength with only 5.9 MPa followed by SWW0.9CB0.3 with only 5.0 MPa. However, SWW0.3CB0.3 shows a steady increment with the splitting tensile strength value reaching up to 7.7 MPa. According to the specified requirements for grade C25 concrete, the targeted splitting tensile strength was 3.5 MPa. So, for the SWW0.3CB0.3, it has actually doubled its performance. The highest splitting tensile strength achieved was 7.7 MPa for SWW0.3CB0.3, surpassing the targeted strength of 3.5 MPa by 200%.

Additional SWW reinforcement lessens the likelihood of cracking and increases the splitting tensile strength by assisting in resisting the tensile forces that arise during loading [17]. As shown in Fig. 14, the 900 g addition of SWW has the lowest splitting tensile strength. This might have happened because of insufficient bonding. The bonding of the SWW to the surrounding concrete matrix determines how well it can increase the splitting tensile strength. The transmission of tensile forces from the SWW to the concrete matrix may be compromised if there is insufficient bonding or poor adhesion between the two materials. Reduced splitting tensile strength may be the result of this weak bonding [16]. In addition, more SWW addition increased the tendency to tangle between themselves and reduced the strength.

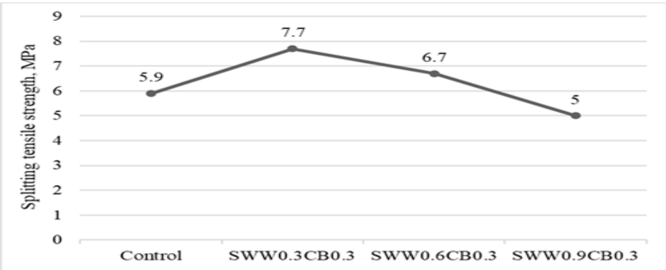

Fig. 14 – Splitting strength for all concrete mixtures

4. CONCLUSIONS

The addition of SWW can help to improve the overall strength of concrete but only at a certain amount. SWW helps distribute the applied loads and increases the load-carrying capacity of the concrete. This results in improved flexural strength, allowing the concrete to withstand higher bending stresses without failure. It also helps resist tensile forces and prevents cracking or failure under tensile loads, improving the tensile strength of the concrete. However, it is essential to note that adding an excessive amount of steel wire to concrete may reduce its strength. Meanwhile, the CB in concrete generally does not have a significant impact only on its physical appearance where all samples become black due to their original color. While there may not be a vast amount of research specifically combining CB and SWW from tires, ongoing efforts in recycling and sustainable materials development continue to explore innovative ways to utilize these materials effectively.

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REFERENCES

[1] Y. Modarres and M. Ghalehnovi, "The Effect of Recycled Steel Fibers from Waste Tires on Concrete Properties," *Civ. Eng. Infrastructures J.*, vol. 56, no. 1, pp. 1–18, 2023.

[2] F. Juveria, P. Rajeev, P. Jegatheesan, and J. Sanjayan, "Impact of stabilisation on mechanical properties of recycled concrete aggregate mixed with waste tyre rubber as a pavement material," *Case Stud. Constr. Mater.*, vol. 18, no. January, p. e02001, 2023.

[3] M. Saidani, D. Saraireh, and M. Gerges, "Behaviour of different types of fibre reinforced concrete without admixture," *Eng. Struct.*, vol. 113, pp. 328–334, 2016.

[4] M. Frančić Smrkić, D. Damjanović, A. Baričević, and M. Uroš, "Experimental and numerical analysis of concrete slabs reinforced with rebar and recycled steel fibers from waste car tyres," *Struct. Concr.*, vol. 24, no. 2, pp. 1807–1820, 2023.

[5] P. Su, M. Li, Q. Dai, and J. Wang, "Mechanical and durability performance of concrete with recycled tire steel fibers," *Constr. Build. Mater.*, vol. 394, no. June, p. 132287, 2023.

[6] S. Gwon, H. Kim, and M. Shin, "Self-heating characteristics of electrically conductive cement composites with carbon black and carbon fiber," *Cem. Concr. Compos.*, vol. 137, no. December 2021, p. 104942, 2023.

[7] A. Musale, A. M. Hunashyal, and A. K. Roopa, "The Effect of Carbon Black, MWCNT and Carbon Fiber on Flexural behavior of cement nano composites," *E3S Web Conf.*, vol. 405, 2023.

[8] ASTM C136/C136M, "Standard test method for sieve analysis of fine and coarse aggregates," *ASTM Int.*, pp. 1–5, 2014.

[9] BS 1881-102, "Method for determination of slump," *Br. Stand.*, 1983.

[10] BS 1881-114, "Methods for determination of density of hardened concrete," *Br. Stand.*, no. December, 1983.

[11] BS EN12390-3, "Compressive strength of test specimens," *Br. Stand.*, 2009.

[12] BS EN 12390-5, "Flexural strength of test specimens," *Br. Stand.*, no. August, pp. 1–22, 2009.

[13] G. Sabih, R. A. Tarefder, and S. M. Jamil, "Optimization of Gradation and Fineness Modulus of Naturally Fine Sands for Improved Performance as Fine Aggregate in Concrete," *Procedia Eng.*, vol. 145, pp. 66–73, 2016.

[14] T. A. Ansari, I. Al Rashdi, T. Shaher, I. Mohammed, A. Amra, and S. Issa, "Effect of Waste Steel Binding Wires on Strength of Concrete," *Int. Res. J. Eng. Technol.*, no. July, pp. 1223–1230, 2021.

[15] A. Sofi and G. Naidu Gopu, "Influence of steel fibre, electrical waste copper wire fibre and electrical waste glass fibre on mechanical properties of concrete," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 513, no. 1, 2019.

[16] Y. Deng, Z. Zhang, C. Shi, Z. Wu, and C. Zhang, "Steel Fiber–Matrix Interfacial Bond in Ultra-High Performance Concrete: A Review," *Engineering*, vol. 22, pp. 215–232, 2023.

[17] G. Fares, A. Alsaif, and A. Alhozaimy, "Hybridization and cost-performance analysis of waste tire steel fibers into high-volume powdered scoria rocks-based ultra-high performance concrete," *J. Build. Eng.*, vol. 72, no. April, p. 106568, 2023.