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Mechanical Properties and Impact Behavior of Hybrid Fiber Reinforced Rubberized Self-Compacting Concrete

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ABSTRACT

The problem of discarded tires has received a lot of attention from many authors. The incorporation of rubber aggregate recycled from waste tires is one of the solutions to this issue. This research is based on evaluating fresh and hardened properties such as slump flow, T500, segregation resistance, L-box tests, compressive strength, impact resistance, and flexural toughness. Rubber aggregate replacements in the self-compacting concrete (SCC) mixes were 10% by volume of fine aggregate. Additionally, both PET and steel fibers are utilized at a volume rate of 0.25%. The outcomes indicate that introducing rubber declines rheological and hardened properties, whereas incorporating hybrid fibers enhances hardened properties such as compressive strength, impact energy, and flexural toughness. The best increase in impact energy was obtained at roughly 166.6% when 0.25% hybrid fibers and 10% rubber were used. 74.21 was the greatest increase in flexural toughness when 0.25% of hybrid fibers were used in SCC. As for the compressive strength, it was the highest by about 11%.

1. Introduction

self-compacting concrete (SCC), a form of concrete, has the ability to coat corners and reinforcement gaps while being poured, eliminating the requirement for vibration or compaction (Stanaszek-Tomal, 2020). The term waste refers to anything that has been discarded, thrown away, or eliminated by its possessor. Rubber is now a crucial substance that is necessary for the progress of human civilization through technology. There are various methods to recycle rubber, like reclaiming technology, surface treatment, grinding and pulverization technology, and devulcanization technology. Worldwide, the usage of natural rubber exceeds 15 million tons per year, and the production of rubber products is over 31 million tons (Akca et al., 2018). (Banerjee & Rooby, 2019) investigated the best method to use waste tire rubber as coarse aggregate in concrete composites. In this study, M25-grade

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concrete cubes were cast with 5, 10, 15, 20, and 25% partial replacement of tire rubber aggregate with coarse aggregate. The results were compared to ordinary M25 grade concrete, which is composed of a 1:1.2:2.7 mixing ratio with w/c. 0.45 and a target mean strength (Nmm^2) of 31.60. It was observed that when rubber replacement level increases, the flexural and compressive strengths decrease when the workability increases in concrete. The way used for the production of lightweight concrete. In this context, (Gerges et al., 2018) studied the effect of recycled rubber powder on concrete. Natural sand was partially replaced by 5%, 10%, 15%, and 20% of recycled rubber powder. Density, compressive strength, split-tension, impact load capacity, and fresh properties were tested. The results showed that increasing rubber content caused a decrease in the compressive strength of concrete. Although rubberized concrete mixtures generally have a lower compressive strength, they have desirable properties such as higher impact resistance, low density, and improved toughness. (Khalil et al., 2015) created concrete samples by replacing sand with varying percentages of 10%, 20%, 30%, and 40% crumb rubber. The impact resistance, as measured by the number of blows at the first and final cracks, rose by roughly 188% and 170%, respectively, with an increase in rubber percentage up to 30%. Subsequently, the impact resistance began to decline, suggesting that the final rubber percentage is 30%. Plastic is a versatile and durable material, known for its lightweight and resistance, which enables it to be processed in various ways and applied across a diverse range of fields such as packaging, automotive, and building construction industries, water desalination, and flood preservation (Corder et al., 2015). Polyethylene Terephthalate (PET) is among the various types of plastic extensively used worldwide (Sharma & Bansal, 2016) (Allawi et al., 2021).

Hybrid fiber-reinforced concrete is a concept that utilizes various types of fibers in concrete mixtures, aiming to produce more efficient and mechanically enhanced concrete. The classification can be determined by the choice of fibers utilized, which may include steel, glass, plastic, polypropylene, carbon, and natural fibers, as well as by the size of the fibers, whether micro or macro, and the form they take, whether smooth or hooked. These variables can lead to distinct behaviors and characteristics in the material (Younis et al., 2018). (Su et al., 2021) the impact of utilizing hybrid fiber-reinforced rubber concrete (HFRC) on mechanical properties was investigated. PVA fiber, measuring 12 mm × 8 μm (length × diameter), and basalt fiber, measuring 18 mm × 12 μm (length × diameter), were used in this study. In comparison to the reference mix, the results showed that adding hybrid fibers of both kinds (basalt fibers and PVA fibers) at ratios of 0.1%, 0.2%, and 0.3% with rubber at ratios of 5%, 10%, and 15% lead to increased compressive, splitting tensile, and flexural strengths. However, using a mixture containing 5% rubber, 0.3% basalt fiber, and 2.0% PVA fiber produced the highest results for compressive strength, splitting tensile strength, and flexural strength, which were 47.9 MPa, 6.63 MPa, and 8.98 MPa, respectively. (Alwesabi et al., 2022) conducted an experimental program to study the effect of two types of hybrid fiber (Polypropylene (PP) and Micro steel (MS) fibers on the compressive toughness of concrete. Tests such as compressive strength, compressive toughness, and toughness index of FRC, as well as density, water absorption, and voids in concrete, were conducted. The results obtained showed an increase in density and a decrease in water absorption and voids, with positive results for the compressive strength of the mixture containing hybrid fibers by 0.9% (pf) and 0.1% (MSF). Also, good results were obtained in the compressive toughness properties of the hybrid FRC mixture. As for the compressive strength properties, they were higher by about 0.321 MPa and 106.5% when the mixture contained a 0.9% (PF) and 0.1% (MSF-FRC) hybrid. Hybrid fibers can sometimes counteract the decrease in compressive strength, improve flexural performance, and significantly reduce time-dependent strains in fiber-reinforced SCC (Li et al., 2021). The goal of this research is to evaluate the performance of hybrid fiber reinforced rubberized concrete in terms of mechanical properties including toughness and impact energy. The rubber aggregate included by 10% replacement ratio (volume of sand) with combination of two types of fibers (PET and hooked ended steel fibers). The produced green self-compacting concrete may introduce a solution of the problem of discarded tires with balance to reduced strengths due to rubber aggregate inclusion.

2. Experimental program

2.1. Materials

Ordinary Portland cement type I from AL-Mas Company in Sulaymaniyah Iraq was used in this study to produce SCC mixes. Tables 1 and 2 list the chemical and physical properties of this type of cement, respectively, which confirm the Iraqi specifications (No. 5-2019). Fine aggregate with a maximum size of 4.75 mm and a specific gravity of 2.62 was used. Coarse aggregate with a maximum size of 10 mm and a specific gravity of 2.6

was used. Tables 3 and 4 show sieve analyses of fine and coarse aggregate. The results appeared within the limits of Iraqi specification No. 45 (No 1984). Silica fume type Mega Add MS (D) is based on ASTM C1240 (ASTM, 2003). Hooked-end steel fibers (HE) with a length of 35 mm and an aspect ratio of 64 were utilized in this study. Polyethylene terephthalate (PET) fiber obtained from waste plastic was utilized. PET properties are listed in Table 5. The recycled crumb rubber aggregate has a specific gravity of 1.1 and a fineness modulus of 2.24. The sieve analysis for the fine, rubber, and coarse aggregate is shown in Figure 1. Steel fibers, PET fiber, and crumb rubber utilized in this study are depicted in Figure 2.

Table 1 – Physical properties of cement

Physical properties	Test result	Limit of Iraqi specification No.5/2019
Fineness using the Blaine method (m2/kg)	3345	≥ 250 m2/kg
Initial setting time (minutes)	126	≥ 45
Final setting time (minutes)	228	≤ 600
Soundness (mm)	1	≤ 10 mm
Autoclave %	0.1	≤ 0.8%
The compressive strength of mortar		
2 days (MPa)	12.6	≥ 10 MPa
28 days (MPa)	45.4	≥ 32.5 MPa

Table 2 – Cement Chemical compositions

Chemical composition	Content % by weight	Limit of Iraqi specification No.5/2019
Silica (SiO_2)	20.05	……..
Alumina (AL_2O_3)	4.76	……..
Iron Oxide (Fe_2O_3)	5.1	……..
Lime (Cao)	62.96	…….
Sulfate (SO_3)	2.42	Not more than 2.8 %
Magnesia (MgO)	3.17	Not more than 5%
Loss of ignition (L.O.I)	1.7	Not more than 4%
Lime saturation factor (L.S.F)	0.97	0.66-1
Insoluble residue (I.R)	0.45	Not more than 1.5 %
Main compounds		
C2S	19.41	
C3S	49.44	
C3A	4.01	
C4AF	14.61	

Table 3 – Physical properties of PET fibers

Physical properties of PET	Description
Color	**Crystalline Green**
Length	**25mm**
Width	**4mm**
Thickness	**0.3**
Specific gravity	**1.3**
Aspect ratio	**20.22**

Table 4 – Sieve analysis of coarse aggregate

Sieve size (mm)	Cumulative passing %	Limit of Iraqi specification No.45/ 1984
20	100	100
14	100	90-100
10	80.7	50–85
5	9	0–10

Table 5 – Sieve analysis of fine aggregate

Sieve size (mm)	Cumulative passing %	Limit of Iraqi specification No.45/ 1984 (Zone 2)
10	100	100
4.75	97.48	90-100
2.36	83.89	75–100
1.18	70.44	55–90
0.6	53.54	35–59
0.3	15.84	8–30
0.15	2.25	0–10

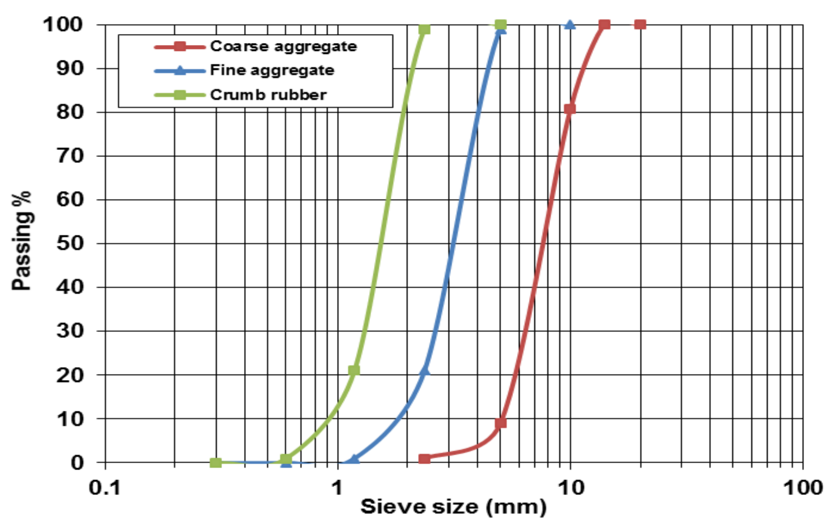

Fig. 1 Sieve analysis of coarse, fine, and crumb rubber aggregate

Fig. 2 Materials used in this study: (A) Steel fiber (B) PET fiber (C) Crumb rubber aggregate.

3. Mix proportions

The design of all mixes was according to the European guidelines (EFNARC, 2005). Rubber particles were added by replacing sand (by volume) at 10% in all rubberized SCC mixes. For hybrid mixes, the volume of fibers was selected to be 0.25% (80% SF and 20% PET) and 0.35% (50% for each PET and SF). Mix proportions are shown in Table 6.

Table 6 – Mixing Proportions (in kg/m3)

NO	MIX	Rubber%	C	G	S	SF	Rubber	PET	SF	W	SP/C
1	SCC	-	400	780	970	60	-	-	-	180	**2%**
2	SCCR	10%	400	780	872	60	40.4	-	-	180	**2%**
3	SCCH2	-	400	780	970	60	-	0.65	15.6	180	**2%**
4	SCCH3	-	400	780	970	60	-	1.63	9.75	180	**2%**
5	SCCH2R1	10%	400	780	872	60	40.4	0.65	15.6	180	**2%**
6	SCCH3R1	10%	400	780	872	60	40.4	1.63	9.75	180	**2%**

4. Casting and curing of specimens

After the concrete mixing process, the provided molds were used to cast cubic, prismatic, and slab specimens. Prior to pouring, the molds were cleaned and oiled. Subsequently, nylon sheets were used to cover all the samples. The mixtures were taken out of the molds 24 hours later, then cured in water tank until the age of testing. Table 7 shows the specifics of the SCC samples.

Table 7 – Details of SCC specimens

Tests	Sample type	Dimensions (mm)	Number
Compressive strength	cube	100 × 100 × 100	18
Impact strength	slab	50cm × 50cm × 50mm	12
Flexural toughness	Prism	100 × 100 × 400	18

5. Mix design

A laboratory rotary mixer with a capacity of 0.1 m^3 was used to prepare all mixtures of SCC. With the exception of PET fibers, HE fibers, and super-plasticizer, which were all prepared and weighed using a delicate balance, all materials were prepared and weighed using a digital balance. Sand and gravel were added to the rotary mixer. After that, cement and silica fume were added and blended together for one minute. Crumb rubber with a specific amount of water was added gradually, and the remaining water was mixed with the superplasticizer and added to the mixer for two minutes. Finally, HE or PET fibers were added gradually to ensure their distribution throughout the mixture. After leaving the combination for two minutes in the mixer.

6. Results and Discussion

6.1. Rheological and hardened properties

6.1.1. Slump flow

All the slump flow results rely on the European standard (EFNARC, 2005). The inclusion of rubber aggregate in the SCC mix resulted in a 1.9% reduction in slump flow values when compared to SCC. The primary reason for the decrease in slump flow results may be attributed to the rough surface and irregular shape of the crumb rubber (Lv et al., 2019). The utilization of hybrid fiber resulted in a 7.6% decrease in slump flow values for SCCH2 and a 7% decrease for SCCH3, as demonstrated in Figure 3. This can be attributed to PET fibers' tendency to aggregate. This aggregation creates clusters, which in turn have an impact on the distribution of concrete followability and lessen the overall workability of SCC (Al-Hadithi et al., 2019). Because of their elevated aspect ratio and the way, they interact with one another, steel fibers can impede the flow of fresh self-compacting concrete (Wang et al., 2020). The crumb rubber with hybrid fiber (SCCH2R and SCCH3R) reduced slump flow by 11.5% and 10.25%, respectively.

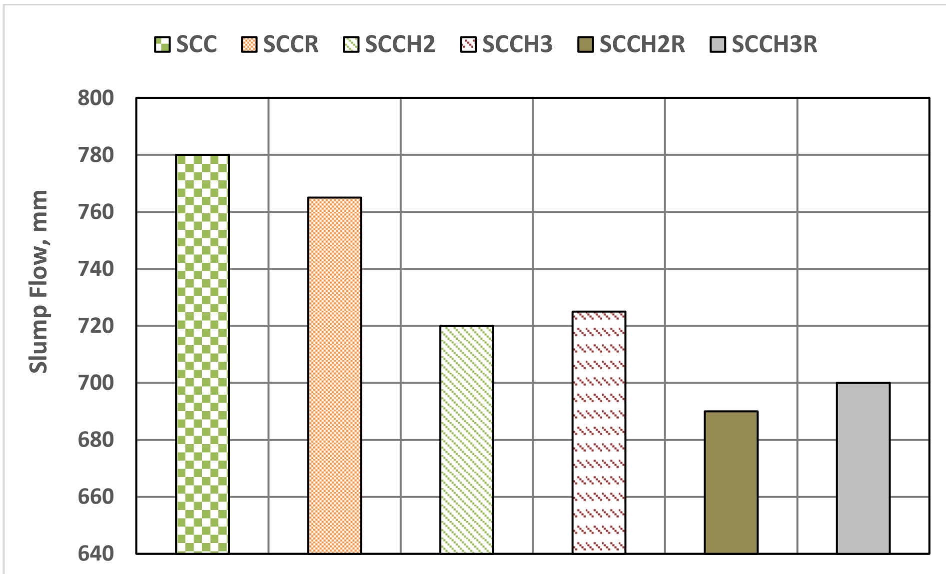

Fig. 3 Slump flow test results

6.1.2. T500

Figure 4 displays the T500 test results. it was observed that the t500 values of rubberized concrete were 15% higher than those of the reference mix. This may be connected to rough surfaces and surfaces with rubber particles having more friction (Bušić et al., 2018). When 0.25% hybrid fibers were added to the SC mix, the T500 values increased from 2.2 seconds for the reference mix to 2.9 and 2.6 seconds. The network activity and the increased surface area of fibers are responsible for the increase in T500 values resulting from the introduction of hybrid fibers (Al-Attar et al., 2018). The highest value of T500 was for the mixture containing hybrid fibers with rubber (SCCH3R).

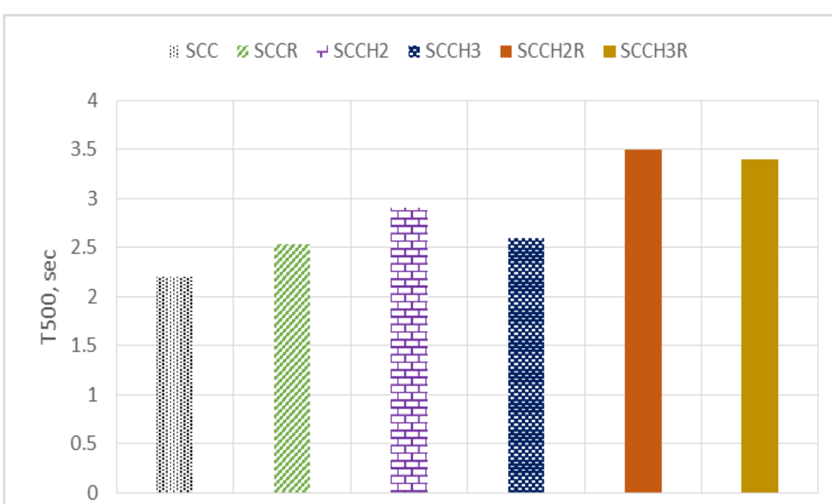

Fig. 4 T500 test results

6.1.3. L-box

According to the results shown in Figure 5, the SCC mixes had a value falling within the range of 0.8 to 1, in accordance with the suggestions made by the EFNARC requirements. The inclusion of 10% rubber particles in the mixture caused a 1.02% decrease in the value of L-box compared to SCC. The sharp edges of crumb rubber, which can lead to blockages and require more energy to pass through (Iqbal et al., 2015). According to the findings, the l-box value showed a decrease of 5.1% and 6.12% for SCCH2 and SCCH3, respectively, compared to the reference mix. On the other hand, when incorporating rubber with the hybrid fibers, there was a more significant decrease in the l-box value.

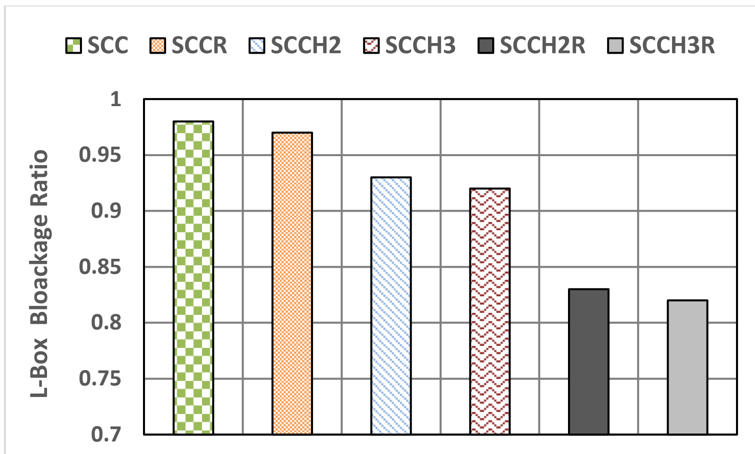

Fig. 5 L-box test results

6.1.4. Segregation resistance

The test is used to evaluate the resistance of SCC against segregation (Jawhar et al., 2023). The segregation index (SI) of a mix including 10% rubber was reduced by 16.7% as compared to SCC, as shown in Figure 6. The appearance of the reduced segregation ratio is mainly caused by the thickening impact of rubber particles (Özaşik & Eren, 2022). When PET and steel fibers are combined, SI will be lower than SCC by 17.5% and 22.5%, respectively. In comparison to SCC, the combination of rubber and hybrid fibers reduces SI by 35% and 27.5% for SCCH2R and SCCH3R, respectively.

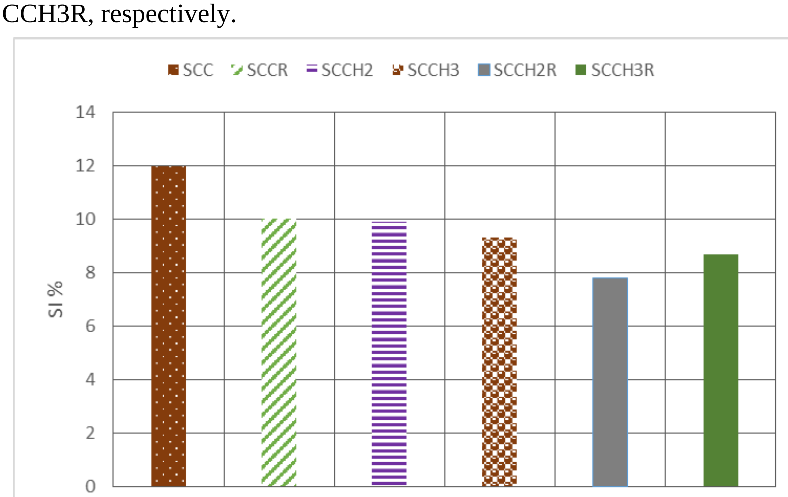

Fig. 6 Segregation resistance test results

6.1.5. Compressive strength

The compressive strength results are illustrated in Figure 7. The compressive strength decreased by 14% with the addition of crumb rubber at 10% content to concrete compared to SCC. The reasons behind this decrease can be attributed to the weak interface between rubber and cement paste, which facilitates the initiation and propagation of microcracks (Mustafa et al., 2019). The inclusion of hybrid fiber led to an increase in compressive strength of 11% and 8.15% for SCCH2 and SCCH3 mixes, respectively. The results revealed that SCCH2R and SCCH3R mixes have a negative effect on compressive strength by 17.4% and 19.8%, respectively, compared to the reference SCC mix. The failure mode in cubic specimens after conducting the compressive strength test is illustrated in Figure 8.

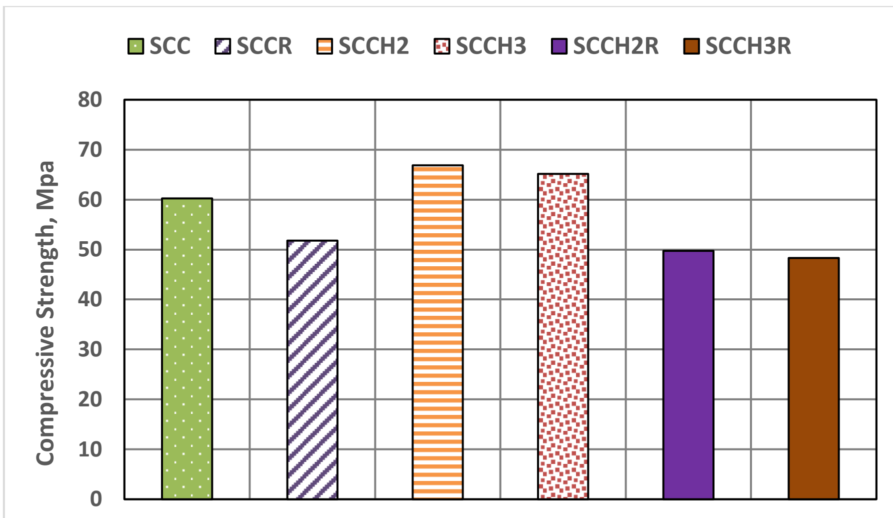

Fig. 7 Compressive strength test results

Fig. 8 Failure modes of cube specimens

6.1.6. *Impact Resistance*

Figure 9 presents the findings of the impact behavior test. The results of all mixes for the first crack impact resistance were similar to SCC, except for the SCCH2R mix, which increased by 50%. The findings suggest that the incorporation of crumb rubber into SCC led to increased impact energy by about 44.4% for ultimate failure. This is due to the rubber particles capacity to absorb the plastic energy that arises when a mass falls from a specific height (Topçu & Avcular, 1997; Emara et al., 2018). By adding hybrid fibers at volume fractions of 0.25% to SCC, the impact of energy required to reach ultimate failure increased by approximately 66.6% and 33.4% for the SCCH2 and SCCH3, respectively. Plastic enhances the flexibility mixes as well as its ductility and capacity to withstand impact loads (Mustafa et al., 2019). Steel fibers strengthen the concrete by resisting these tensile stresses and preventing cracking and failure (Abid et al., 2021). Figure 4-19 demonstrates that the SCCH2R mix had the highest capacity for energy absorption, as evidenced by the significant improvement in the impact resistance that observed when rubber particles were added to the hybrid fibers at the stage of ultimate failure compared to SCC mixtures with no crumb rubber and both types' fibers.

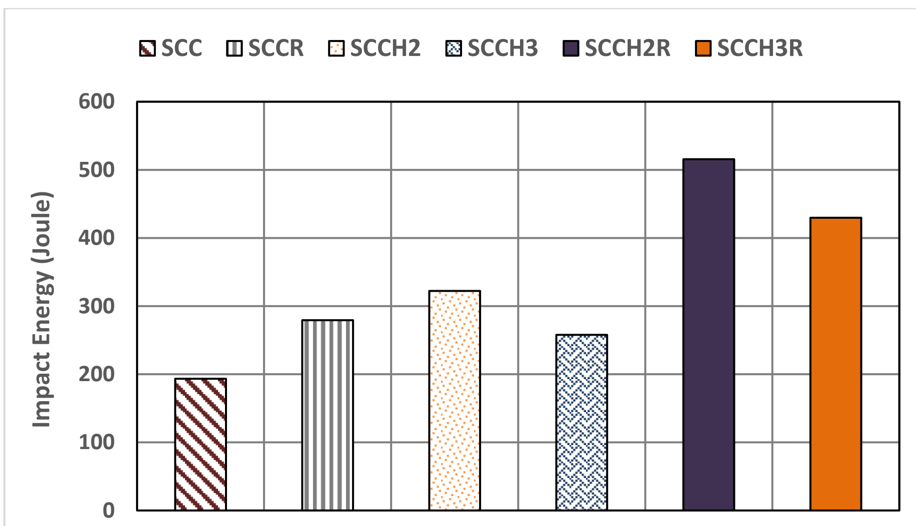

Fig. 9 Average impact energy at ultimate failure of concrete slabs

6.1.7. *Flexural toughness*

Figures 10 to 15 illustrates the relationship between load and deflection, which was established for all SCC mixtures to attain flexural toughness according to specification ASTM C1018. Compared to plain concrete, crumb rubber concrete displayed a slight decrease in toughness. This reduction may be linked to the notable decrease in load-carrying capacity and ductility of the prism (Ismail & Hassan, 2017). Compared to the SCC, the hybrid fiber mixtures SCCH2 and SCCH3 exhibited a 31.27% and 74.21% increase, respectively, in the area under the curve. While the incorporation of hybrid fiber and rubber into the concrete mixture SCCH3R resulted in a good improvement of the area under the curve, on the contrary, the SCCH2R mixture showed a negative effect on flexural toughness. Table 8 indicates that the flexural toughness of SCCH3 is larger compared to the flexural toughness of other samples. The potential cause for the increase in flexural toughness in this mixture could be due to the adequate bonding between plastic waste fibers and steel fibers with the surrounding concrete matrix. This bond facilitates stress transfer between the fibers and the matrix, resulting in a more uniform distribution of loads.

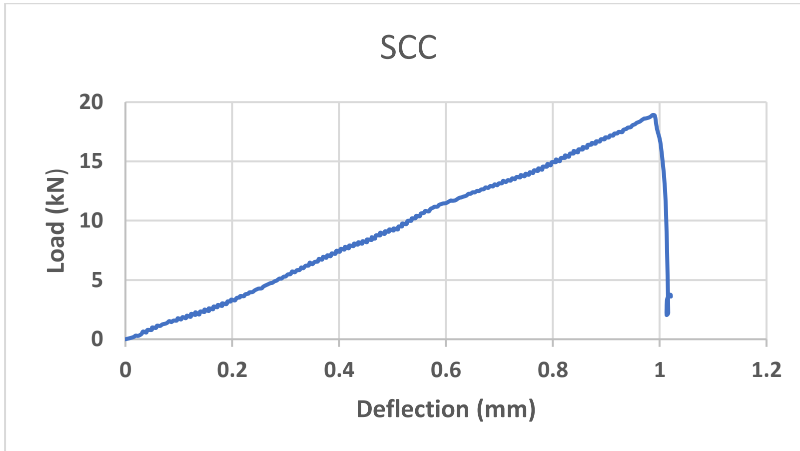

Fig. 10 Load -deflection curve for SCC mix

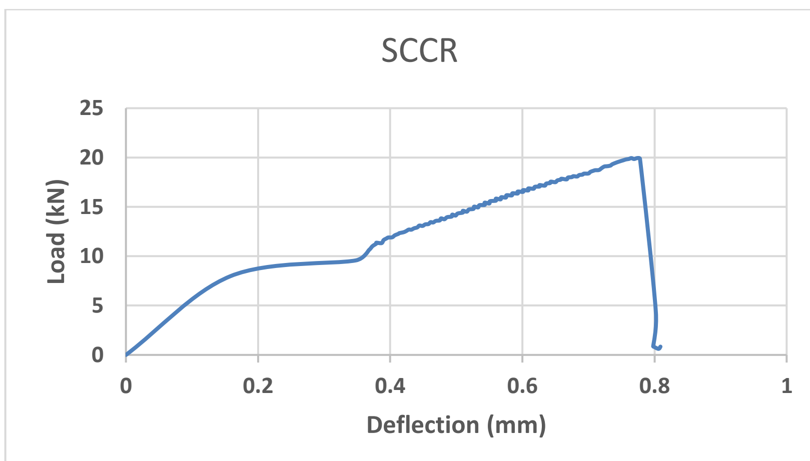

Fig. 11 Load -deflection curve for SCCR mix

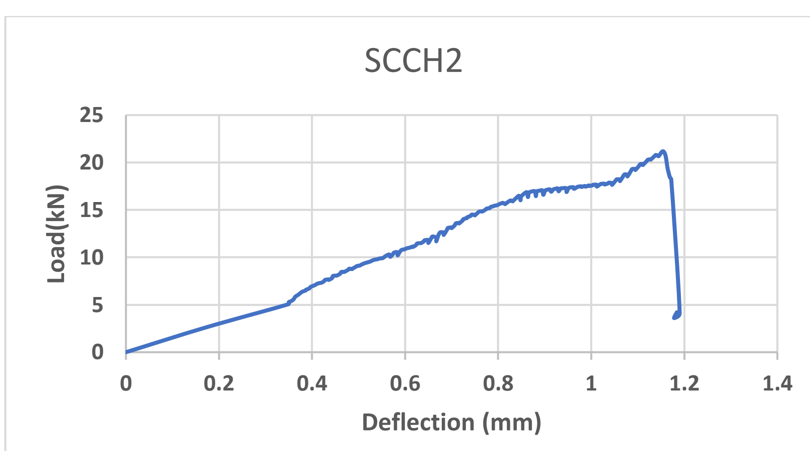

Fig. 12 Load -deflection curve for SCCH2 mix

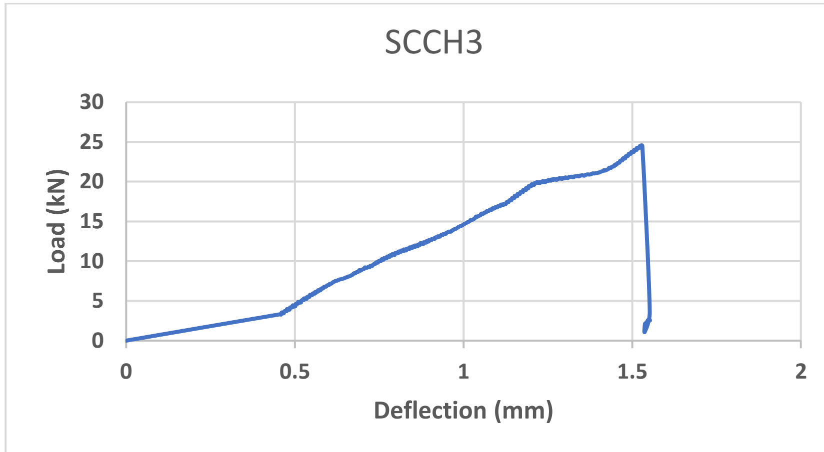

Fig. 13 Load -deflection curve for SCCH3 mix

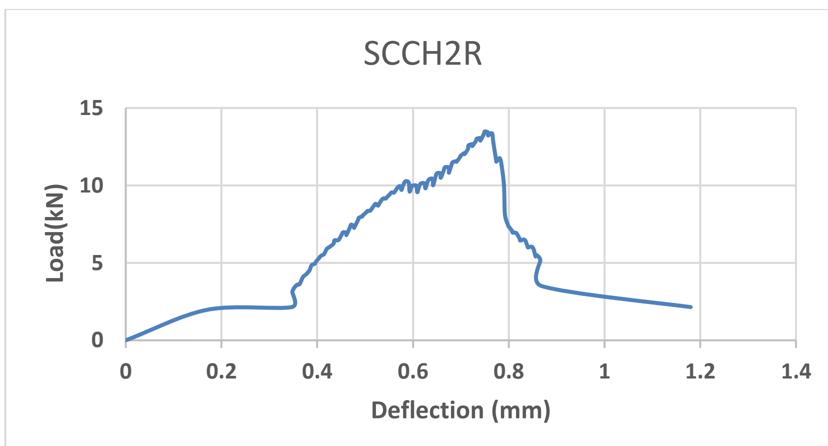

Fig. 14 Load -deflection curve for SCCH2R mix

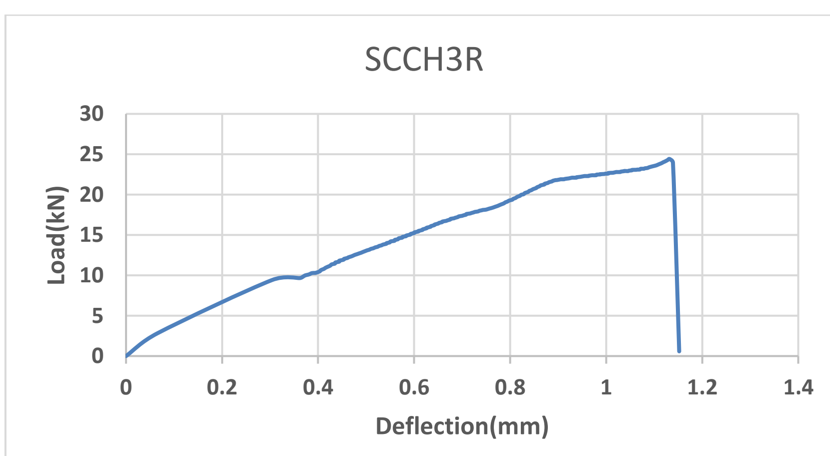

Fig. 15 Load -deflection curve for SCCH3R mix

Table 8 – Flexural toughness results

Mix	Flexural toughness (kN.mm)	Change %
SCC	9.5	**-**
SCCR	9.27	**-2.42**
SCCH2	12.47	**31.26**
SCCH3	16.55	**74.21**
SCCH2R	5.9	**-37.89**
SCCH3R	16.23	**70.84**

7. Conclusions

1- When rubber aggregate is included in the SCC mix, its workability is reduced. Moreover, the results indicate an even greater reduction in workability when hybrid fibers are combined with a rubber SCC mix. The same applies to the l-box results.
2- The addition of rubber aggregate caused a decrease in the compressive strength of SCC, while incorporating hybrid fibers led to an increase of approximately 11% and 8.15%, respectively.
3- A significant improvement was observed in the low-velocity impact strength of all slabs when compared to plain slabs. The slab with rubber particles and a hybrid fiber content of 0.25% demonstrated the most significant rise in impact energy compared to the control slab, showing an increase of approximately 166.67%.
4- The flexural toughness is diminished by adding rubber aggregate to SCC mixture. Nonetheless, enhancements in flexural toughness were observed in contrast to the SCC blend, particularly with the inclusion of hybrid fibers.

References

Abid, S. R., Gunasekaran, M., Ali, S. H., Kadhum, A. L., Al-Gasham, T. S., Fediuk, R.,Vatin, N., & Karelina, M. (2021). Impact performance of steel fiber-reinforced self-compacting concrete against repeated drop weight impact. *Crystals*, 11(2), 91.

Akca, E., Gursel, A., & Sen, N. (2018). A review on devulcanization of waste tire rubber. *Periodicals of engineering and natural sciences*, *6*(1), 154-160.

Al-Attar, T. S., Daoud, S. F., & Dhaher, A. S. (2018). Workability of Hybrid Fiber Reinforced Self-Compacting Concrete. *Engineering and Technology Journal*, *36*(2), 111-116.

Al-Hadithi, A. I., Noaman, A. T., & Mosleh, W. K. (2019). Mechanical properties and impact behavior of PET fiber reinforced self-compacting concrete (SCC). *Composite Structures*, *224*, 111021.

Allawi, A. H., AL-Hadithi, A. I., & Mohmoud, A. S. (2021). Effects of Waste Plastic PET Fibers on The Fresh and Hardened of Normal Concrete. *Iraqi Journal of Civil Engineering*, *15*(1), 47-58.

Alwesabi, E. A., Bakar, B. A., Alshaikh, I. M., Abadel, A. A., Alghamdi, H., & Wasim, M. (2022, March). An experimental study of compressive toughness of Steel–Polypropylene hybrid Fibre-Reinforced concrete. In *Structures*, *37*, 379-388.

ASTM C1018 (1997). Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading), *American Society for Testing Materials*.USA.

ASTM, C1240 (2003). Standard specification for silica fume used in cementitious mixtures. *U American Society for Testing Materials.USA.*

Banerjee, S., & Rooby, J. (2019). Strength Properties of Tyre Rubber Concrete. *EXTRACTION*, *5*, 10.

Bušić, R., Miličević, I., Šipoš, T. K., & Strukar, K. (2018). Recycled rubber as an aggregate replacement in self-compacting concrete—literature overview. *Materials*, *11*(9), 1729.

EFNARC, Specifications and guidelines for self-compacting concrete, in:European Federation of Producers and Applicators of Specialist Products for Structures, 2005.

Corder, G. D., Golev, A., & Giurco, D. (2015). "Wealth from metal waste": translating global knowledge on industrial ecology to metals recycling in Australia. *Minerals Engineering*, *76*, 2-9.

Emara, M. A., Eid, F. M., Nasser, A. A., & Safaan, M. A. (2018). Prediction of self-compacting rubberized concrete mechanical and fresh properties using Taguchi method. *J Civil Environ Eng*, *8*(301), 2.

Gerges, N. N., Issa, C. A., & Fawaz, S. A. (2018). Rubber concrete: Mechanical and dynamical properties. *Case Studies in Construction Materials*, *9*, e00184.

Iqbal, S., Ali, A., Holschemacher, K., & Bier, T. A. (2015). Mechanical properties of steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC). *Construction and Building Materials*, *98*, 325-333.

Iraqi specifications No. 5. (2019). Portland Cement. *Central Organization for Standardization and Quality Control, Ministry of Planning*.

Iraqi Specifications No. 45. (1984). Aggregate from natural sources for concrete. *Central Organization for Standardization and Quality Control, Ministry of Planning*.

Ismail, M. K., & Hassan, A. A. (2017). An experimental study on flexural behaviour of large-scale concrete beams incorporating crumb rubber and steel fibres. *Engineering Structures*, *145*, 97-108.

Jawhar, A. A., Al-Hadithi, A., & Mansoor, Y. A. (2023). Investigate the Fresh and Hardened Properties of Shotcrete Concrete Contains Different Types of Plastic Fibers. *Iraqi Journal of Civil Engineering*, *16*(2), 90-100.

Khalil, E., Abd-Elmohsen, M., & Anwar, A. M. (2015). Impact resistance of rubberized self-compacting concrete. *Water Science*, *29*(1), 45-53.

Li, K. F., Yang, C. Q., Huang, W., Zhao, Y. B., Wang, Y., Pan, Y., & Xu, F. (2021). Effects of hybrid fibers on workability, mechanical, and time-dependent properties of high strength fiber-reinforced self-consolidating concrete. *Construction and Building Materials*, *277*, 122325.

Lv, J., Zhou, T., Li, K., & Sun, K. (2019). Shrinkage properties of self-compacting rubber lightweight aggregate concrete: Experimental and analytical studies. *Materials*, *12*(24), 4059.

Mustafa, M. A. T., Hanafi, I., Mahmoud, R., & Tayeh, B. A. (2019, August). Effect of partial replacement of sand by plastic waste on impact resistance of concrete: experiment and simulation. In *Structures*, 20, 519-526.

Özaşik, N., & Eren, Ö. (2022). Influence of recycled polyethylene terephthalate fibres on plastic shrinkage and mechanical properties of concrete. *Frontiers of Structural and Civil Engineering*, *16*(6), 792-802.

Sharma, R., & Bansal, P. P. (2016). Use of different forms of waste plastic in concrete–a review. *Journal of Cleaner Production*, *112*, 473-482.

Stanaszek-Tomal, E. (2020). Bacterial concrete as a sustainable building material?. *Sustainability*, *12*(2), 696.

Su, Q., Xu, J. M., & Wang, Y. D. (2021). Mechanical Properties of Hybrid Fiber Reinforced Rubber Concrete. *Materials*, *14*(20), 6028.

Topçu, I. B., & Avcular, N. (1997). Collision behaviours of rubberized concrete. *Cement and concrete research*, *27*(12), 1893-1898.

Wang, J., Dai, Q., Si, R., Ma, Y., & Guo, S. (2020). Fresh and mechanical performance and freeze-thaw durability of steel fiber-reinforced rubber self-compacting concrete (SRSCC). *Journal of Cleaner Production*, *277*, 123180.

Younis, K. H., Ahmed, F. S., & Najim, K. B. (2018, September). Effect of recycled-steel fibers on compressive strength and shrinkage behavior of self-compacting concrete. In *2018 11th International Conference on Developments in eSystems Engineering (DeSE), Cambridge, UK* (pp. 268-272). IEEE.