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Mechanical properties of sustainable green self-compacting concrete incorporating recycled waste PET: A state-of-the-art review

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Abstract. Majority of the plastic produced each year is being disposed in land after single-use, which becomes waste and takes up a lot of storage space. Therefore, there is an urgent need to find alternative solutions instead of disposal. Recycling and reusing the PET plastic waste as aggregate replacement and fiber in concrete production can be one of the eco- friendly methods as there is a great demand for concrete around the world, especially in developing countries by raising human awareness of the environment, the economy, and Carbon dioxide (CO_2) emissions. Self-compacting concrete (SCC) is a key development in concrete technology that offers a number of attractive features over traditional concrete applications. Recently, in order to improve its durability and prevent such plastics from directly contacting the environment, various kinds of plastics have been added. This review article summarizes the latest evident on the performance of SCC containing recycled PET as eco-friendly aggregates and fiber. Moreover, it highlights the influence of substitution content, shape, length, and size on the fresh and properties of SCC incorporating PET plastic. Based on the findings of the articles that were reviewed for this study, it is observed that SCC made of PET plastic (PETSCC) can be employed in construction era owing to its acceptable mechanical and fresh properties. On the other hand, it is concluded that owing to the lightweight nature of plastic aggregate, Reusing PET waste in the construction application is an effective approach to reduces the earthquake risk of a building.

Keywords: PET aggregate; PET fiber; SCC containing PET plastic (PETSCC); Self-compacting concrete (SCC)

1. Introduction

Globally, the quantity of plastics of all kinds consumed each year has significantly increased. Landfilling plastic products after their usage endangers the environment. Plastic is not biodegradable and does not dissolve or decompose in water or soil. On the other side, it contaminates water and soil. An enormous amount of plastic waste (PW) is produced by the manufacturing process, municipal solid waste (MSW), and service sectors. Plastic production has increased steadily over the last 50 years, rising from 50 million tons in 1976 to 367 million tons in 2020 (Plastics Europe 2020). Fig. 1 illustrates the plastic waste treatment per country in 2018, where 29.1 million tons of plastic consumption were gathered to be treated. Mechanically recycled plastic waste was nearly 32.5% of all waste plastic, 42.6% was recovered for energy, and the remaining 24.9% was sent to landfills (Plastics Europe 2020). Rapid urban growth has resulted in an alarming increase in the number of PWs such as polyethylene terephthalate (PET), various forms of rubber, steel, basalt, glass, paper, and so on. Such production of PWs pollutes the environment in all parts of the world (Al-Salem *et al*. 2009, Guerrero *et al*. 2013, Iucolano *et al*. 2013, Al-Tayeb *et al*. 2020, Fediuk *et al*. 2020, Tayeh *et al*. 2021).

PET is the most commonly used thermoplastic, obtained in large quantities from plastic bottles made for beverage bottles and mineral water (Choi *et al*. 2005, Frigione 2010). The general properties of PET are crystal clear, good strength, reliability, thermal and chemical endurance, and resistance to corrosion and decay (Zhang and Wen 2014). Because of these properties, the use of PET containers has increased worldwide, even though the recycling rate of PET containers is much lower (Foti 2013). The imbalance in PET container production and recycling places a significant overload on restricted landfills. Because recycling and reusing PET require a lot of energy. Therefore many researches have been performed to consider the influence of PET waste plastic on concrete and construction materials as a binder, filler material, recycled fiber, or substitution of fine or coarse aggregate (Kardon 1997, Ohama 1997, Marzouk *et al*. 2007, Ochi *et al*. 2007, Siddique *et al*. 2008, Choi *et al*. 2009, Remadnia *et al*. 2009, Paliwal and Maru 2017, Fayed and Mansour 2020, Al-Tayeb *et al*. 2022). The high amount of sand and gravel being used in the manufacturing of concrete has led to a considerable environmental problem, such as significant reductions in natural resources and Carbon dioxide (CO_2) emissions throughout extraction (Al-Tayeb *et al*. 2019, Almeshal and Tayeh 2020, Akkouri *et al*. 2022). As a result, construction is an important industry that can gain an advantage from

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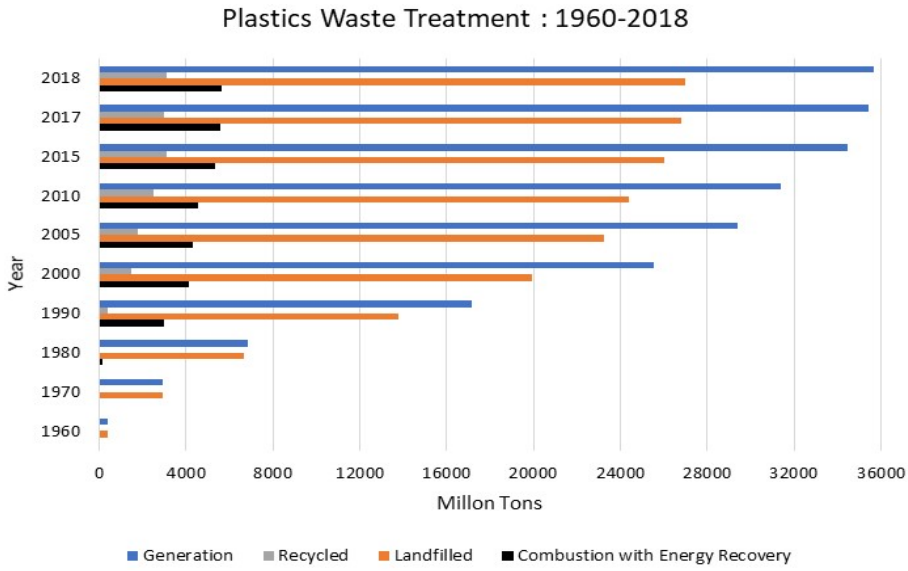


Fig. 1 Plastic waste treatment in 2018 by EU28+NO/CH (Plastics Europe 2020)

waste recycling, which can be utilized as a building material (Klöckner 2013, Behera *et al*. 2014, Mohammadinia *et al*. 2019, Almeshal *et al*. 2020, Ashok *et al*. 2020, Al-Tayeb *et al*. 2021).

Self-compacting concrete is considered a concrete that can flows and penetrate by its own weight without the use of external power and can be easily distributed through spaces between reinforcing bars (Djelloul *et al*. 2018, Gholhaki *et al*. 2018, Majeed *et al*. 2021). This type of concrete has excellent workability properties and can be employed to fill forms with complicated shapes, as well as deep and narrow parts (Ahari *et al*. 2015). The materials utilized in normal concrete are also used in the production of SCC, with the exception that SCC requires a larger percentage of ultra-fine materials (i.e., fly ash, limestone powder and silica fume (Hilmioglu *et al*. 2022). These substances are essential for the enhancement of the stability and workability of the concrete matrix. Furthermore, the inclusion of chemical admixtures (superplasticizers) is important for achieving the flowability of the mixture. The cohesiveness and segregation resistance of mixtures can be gained by introducing a suitable superplasticizer (Han and Yao 2004, Dehwah 2012). Moreover, SCC eliminates noise vibration throughout the placement, improves homogeneity, increases productivity due to faster construction, and improves the working environment. In recent decades, waste PET has been facilitated as fine and coarse aggregate and fiber in SCC (Madandoust *et al*. 2014, Milehsara *et al.* 2015, Kantar *et al*. 2017, Sadrmomtazi and Tahmouresi 2017, Aswatama *et al*. 2018, Khalid *et al*. 2018, Al-Hadithi *et al*. 2019, Mohammed *et al*. 2019, Ayub *et al*. 2021, Hasan-Ghasemi and Nematzadeh 2021, Basser *et al*. 2022).

A review study regarding the usage of PET plastic as a fiber or as a substitution of aggregate in cementitious concrete composites preparation is available in the literature (Chavan and Rao 2016, Sulyman *et al*. 2016). However, there is currently no review on the incorporation of PET plastic as fiber and shredded particles into the formation of SCC to produce a PET self-compacting concrete (PETSCC) mixture. The main goal of this comprehensive review is to concentrate on the most current developments in the assessment of PET plastic in SCC production. In contrast to normal concrete, this paper deals with the fresh characteristics of PETSCC such as flowability, passing ability, viscosity, and segregation resistance of concrete mixture via slump flow diameter test, slump flow time test, L-box test, the V-Funnel test and the J-ring test. Moreover, the different mechanical characteristics of PETSCC, for instance, compressive strength, tensile strength, Young's modulus, and flexural strength were also extensively reviewed.

2. Environmental and economic impact

Annually, one million PET plastic bottles are produced every minute. Most produced plastic bottles are designed for single use and then thrown away. The existence of plastic on earth will pollute it. Moreover, in the ocean, plastic has an adverse effect on the lives of sea creatures (Aswatama *et al*. 2018). Due to plastic waste, every year, nearly 100,000 sea mammals and more than one million sea birds die. Furthermore, burning plastic also contains toxic chemical additives that cause serious health problems. On the other hand, it was found that Plastic waste costs $13 billion in economic damage to marine ecosystems annually. These include losses to fisheries and tourism sectors, as well as cleaning costs (UNEP 2014). Thus, it is crucial to reduce PWs and their adverse environmental and economic effect through reusing and recycling. For this purpose, many countries have limited the usage of plastic bottles, while others have introduced recycling methods (Saikia and De Brito 2012). Recycling is an important strategy that helps the environment. It preserves natural resources, reduces the need for raw materials, and prevents usable materials from being dumped into landfills. Moreover, waste recycling reduces the carbon emissions by extending the life of materials and giving them additional uses before they become waste.

3. Mix design of SCC

The crucial step in the production of concrete is the mix design. The mix design of SCC is one of the most challenging steps concerning the selection of its components (Shi *et al*. 2015). SCC should provide high flowability and high segregation resistance, which can be achieved by using a higher percentage of fine aggregate and filler materials than normal concrete (Li *et al*. 2005). The available mix design methods for SCC in the literature from 1995 to 2022 are tabulated in Table 1. Based on the concepts, these approaches can be sorted into six classes: empirical mix design method, close aggregate packing, statistical factorial model, compressive strength method, Eco-SCC, and rheology of paste methods.

3.1 Empirical mix design method

This type of mix design method is applied to SCC by utilizing different concrete constituents. The performance of SCC is greatly influenced by the properties of aggregate content, water, cementitious, and superplasticizer dosage. Okamura and Ozawa (1995) proposed this type of mix design method for SCC. Initially, the aggregate content is fixed. Then, adjustments are made to the water-to-powder ratio and superplasticizer dosage to enhance SCC's workability. Although this approach is easy to apply, it comes with certain disadvantages when employed in the design of self-compacting concrete (SCC) mixes. This is primarily due to its demand for a significant quantity of cement powder, resulting in elevated production costs. Yoshinobu *et al*. (2003) developed Okamura's mix design method by fixing the amount of fine aggregate, water to powder ratio, and dosage of superplasticizer. Compared to Okamura's method, this method is applicable to different qualities of powders and coarse aggregates. (Khaleel and Razak 2014) presented a mix design method for self-compacting metakaolin concrete with coarse particles of varying characteristics that was similar to Yoshinobu's method. The use of different coarse aggregates and metakaolin in concrete has been demonstrated to be effective in creating SCC.

In summary, an essential benefit of Empirical mix design method is its simplicity, but more experimental tests are required to gain appropriate behavior for existing ingredients and suitable mix proportions. Furthermore, modifications in raw materials will require extensive re-testing and optimization.

3.2 Compressive strength mix design method

This kind of mix design method calculates the amount of concrete components according to the desired strength of concrete. (Kheder and Al Jadiri 2010) introduced a straightforward approach for the design of concrete mixtures. Their approach is based on the ACI 211.1 (ACI 211.1 1991) standard for proportioning traditional concrete

Table 1 An overview of mix design methods for SCC

Classification	Refs.	Year	Main properties
Empirical mix design method	Okamura and Ozawa (1995)	1995	At the beginning, fix the amount of aggregate, then adjust the water to binder ratio and superplasticizer dosage to achieve self-compatibility.
	Yoshinobu *et al*. (2003)	2003	Fixing the amount of fine aggregate, water to powder ratio, and dosage of superplasticizer.
	Domone (2009)	2009	Create the best prediction of the mix proportion for a particular set of desired properties, and then perform trial mixes to prove it.
	Khaleel and Razak (2014)	2014	The work was divided into three stages: paste, mortar, and concrete, with the coarse aggregate content adjusted.
Compressive strength mix design method	Kheder and Al Jadiri (2010)	2010	In this method, ACI 211.1 and EFNARC were used to make normal concrete and SCC, respectively.
	Dinakar (2012)	2012	Based on the strength requirements of SCC by taking into consideration the efficiency of different contents of fly ash.
	Dinakar *et al*. (2013)	2013	Based on the strength requirements of SCC by taking into consideration the efficiency of different content of GGBFS.
Statistical factorial mix design model	Khayat *et al*. (2000)	2000	Gain the optimum statistical correlations among five mixed variables and concrete properties.
Statistical factorial mix design model	Khayat *et al*. (2000)	2000	Gain the optimum statistical correlations among five mixed variables and concrete properties.
	Sonebi (2004)	2004	The researchers proposed a factorial design model for producing SCC by partly substituting of cement by fly ash.
	Ozbay *et al*. (2009)	2009	Based on the Taguchi method for assessing mixture variables of high strength SCC.
	Bouziani (2013)	2013	The influence of three different kinds of fine aggregate on the characteristics of SCC was assessed by the statistical factorial method.

Table 1 Continued

Classification	Refs.	Year	Main properties
Rheology of paste mix design method	Saak *et al*. (2001)	2001	Presented a mixed design method for SCC named (Segregation-controlled) to avoid aggregate segregation.
	Bui *et al*. (2002)	2002	Proposed a paste rheology model based on both the liquid state and blocking state of concrete to generate the least volume of paste for SCC.
	Nielsson and Wallevik (2003)	2003	The introduced method is based on reducing the viscosity to gain the best fresh properties.
	Ferrara *et al*. (2007)	2007	Based on the paste rheology model for designing Steel fiber-reinforced SCC.
	Wu and An (2014)	2014	Proposed mix design of SCC based on pure limestone without cement content.
	Abo Dhaheer *et al*. (2016)	2016	The mix Design depends on rheological properties for producing SCC with ractical guidelines.
	Li *et al*. (2022)	2022	Enhanced the mix design by using prediction accuracy formula method and experimental results
	Li *et al*. (2021)	2021	Developed an equivalence model for binary and ternary powders with the same parameters.
Close aggregate packing mix design method	Su *et al*. (2001)	2001	Using packing factor to optimize the percentage of aggregate in mix design.
	Hwang and Tsai (2005)	2005	In a proposed densified mixture design algorithm method, fly ash was applied as sand to fill gaps among aggregate in the mix proportion.
	Chen *et al*. (2013)	2013	The mixture proportion of SCC is based on a "densified mixture design algorithm" (DMDA).
	Sri Rama Chand *et al*. (2017)	2017	With and without steel fibers, the compressible packing model was utilized to study the packing density of recycled aggregate SCC.
Eco-SCC mix design method	Long *et al*. (2015)	2015	Three environmental effect indices were combined to produce the Eco-SCC mixture.
	Alyamac *et al*. (2017)	2017	Eco-efficient SCC mix was achieved by using the marble powder as a partial substitution of cement.

and the EFNARC (EFNARC 2005) standard for SCC proportioning. There method states that the quantity of coarse aggregates depends on factors such as the maximum aggregate size and the fineness modulus of the fine aggregate. Likewise, the determination of water content in the mixture is predicated upon considerations of both the maximum aggregate size and the desired concrete strength. Dinakar (2012) proposed a mix design method for SCCs containing fly ash; and Dinakar *et al*. (2013) proposed a similar method for granulated blast-furnace slag (GGBS) using efficiency factor.

The strength design method offers a simple and exact procedure to determine concrete mix proportions, reducing the need for trial mixes. It considers factors like aggregate gradation and pozzolanic materials to assess the characteristics of SCC. However, a drawback is that it requires adjustments for all ingredients, including sand, coarse aggregate, superplasticizers, and water, to attain the ideal mixing proportions.

3.3 Statistical factorial mix design method

This practical approach is devoted to determining the impact of various important parameters on the properties of SCC. Consequently, the relative relevance of major mix variables can be evaluated in terms of the amount of concrete components such as cement, aggregate, mineral admixtures, water per powder ratio, and amount of superplasticizer as well as their combined impact on the mechanical properties of SCC mixes (Bouziani 2013).

The statistical factorial design method is applicable across a broad range of mixture proportions, offering an effective way to assess the impact of essential factors on the properties of SCC. This comprehension can simplify the testing process needed to enhance SCC, thereby minimizing the resources needed to achieve an equilibrium between the various factors that influence flowability, deformability, stability, and strength. Nevertheless, the creation of statistical associations demands extensive laboratory experimentation on existing raw materials.

3.4 Rheology of paste mix design method

The rheology of paste method, which is based on the fresh qualities of mortar and the proportion and physical characteristics of coarse aggregate, can be used to evaluate the workability of SCC. An "rheology of paste mix design method" was proposed by Saak *et al*. (2001). According to the method, fresh concrete's segregation resistance and workability were strongly dependent on the cement paste matrix rheology, given a specified particle size distribution and aggregate volume fraction. In an extension of Saak's concepts, Bui *et al*. (2002) included the effects of the volume ratio of aggregates (and pastes), the particle size distribution, and the ratio of fine to coarse aggregate. Subsequently, this method was further advanced by incorporating the influence of steel fibers into the concrete mix design process (Ferrara *et al*. 2007). Li *et al*. (2022) stated that the working performance of SCC can be predicted by rheological paste method.

The application of this method seems encouraging in the design of fiber-reinforced SCC mixtures with selected fresh state properties and a variety of steel fiber ratios and types. Moreover, it can produce a mix design for SCC incorporating pure limestone powder without cement content.

3.5 Close aggregate packing mix design method

This kind of mix design method evaluates the mix proportion by obtaining the minimum voids among aggregate by using packing factor and filling gaps among aggregate by paste. The packing factor calculates the percentage of aggregate which affects the strength, flowability, and pass ability of SCC. Su *et al*. (2001) introduced a mix design methodology for self-consolidating concrete (SCC), utilizing a packing factor (PF). This approach aimed to effectively fill the void spaces within the loosely arranged aggregate matrix with binder paste (Su *et al*. 2001).

This approach is characterized by its simplicity and reduced requirement for binders. However, it is important to note that the self-consolidating concrete (SCC) produced through this method is susceptible to segregation, a prevalent issue encountered in construction practices.

3.6 Eco-SCC mix design method

Eco-SCC (Self-Consolidating Concrete) mix design refers to the process of creating a concrete mixture that is both highly workable and environmentally friendly. an eco-friendly mix design aims to minimize the environmental impact of concrete production by using sustainable materials such as, limestone powder, GGBS, and fly ash in the mixture. Because Eco-SCC has a lower paste volume, achieving the appropriate flowability becomes hard, and it is more susceptible to blockage. To decrease the possibility of blockage, the overall volume of coarse aggregate must be decreased (Mueller *et al*. 2016).

The eco-SCC method faces difficulty in attaining desired concrete properties due to a high water-to-powder ratio and limited cement substitution. Careful additive determination is necessary. Thus, the close aggregate packing mix design is advisable for desired concrete strength and workability.

4. Production and preparation of PET plastic as aggregate and fiber

Recently, the incorporation of waste PET in SCC has been extensively studied. Recycled PET plastic was employed in SCC in two different forms: (i) plastic fiber (PF) which was used in fiber-reinforced SCC (FRSCC) and (ii) plastic aggregate (PA) which was substituted for natural aggregate. The fiber is prepared manually by cutting the plastic drinking bottles using a scissors or paper and CD's shredder machine for generating plastic fibers (As'ad *et al*. 2011, Madandoust *et al*. 2014, Sadrmomtazi and Tahmouresi, 2017, Al-Hadithi *et al*. 2019, Khan and Ayub 2020, Ayub *et al*. 2021) or by modifying fiber waste PET plastic and producing fiber (Siddique *et al*. 2008). On the other hand, PA is obtained from the crushing of plastic bottles by utilizing a crusher machine and then sieving it to obtain a favorite size fraction (Sadrmomtazi *et al*. 2016, Hama and Hilal 2017, Al-Hadithi *et al*. 2019). Furthermore, PET waste of appropriate sizes was gathered from plastic waste treatment plants (Safi *et al*. 2013). In such cases, it is just needed to sieve into a suitable size range at the lab.

5. Utilization of PET plastic as aggregate and fiber in SCC

Similar to the traditional concrete, SCC has several drawbacks (i.e., low ductility, low tensile strength, high weight, low energy absorption, and the presence of soluble salts). Because of these drawbacks or disadvantages, civil engineers have been prompted to use plastic waste as fiber in SCC to improve the ductility, impact strength, tensile strength and prevent cracks (As'ad *et al*. 2011, Madandoust *et al*. 2014, Sadrmomtazi and Tahmouresi 2017, Ganaw *et al*. 2018, Al-Hadithi *et al*. 2019, Khan and Ayub 2020, Ayub *et al*. 2021). Madandoust *et al*. (2014) utilized PET fibers in SCC and evaluated its fresh and hardened properties. The study shows that 3 kg/m^3 of PET fiber can be regarded as proper content concerning such properties of SCC. The mechanical properties of self-compacting rubberized concrete (SCRC) incorporating PET fibers were investigated by Ayub *et al*. (2021). It was concluded that PET fiber, as reinforcement, enhances the response of concrete in terms of compression and flexural strength. It is conceivable that a lightweight, plastic-based concrete mixture can be developed for earthquake-resistant building constructions. incorporating waste PET particles as aggregate has a lower dead weight, which reduces a building's risk of earthquakes, and it can help in designing earthquake- resistant (Akçaözoğlu *et al*. 2010, Saikia and de Brito 2014). Table 2 illustrates the kinds and utilization of PET waste in the production of SCC mixtures.

6. Rheological properties of SCC incorporating recycled PET as fiber and aggregate

The rheological characteristics of SCC can be measured by performing the tests outlined in the "European Federation of National Associations Representing for Concrete" (EFNARC) guidelines for SCC (EFNARC 2005). The most common tests performed on the fresh and rheological behavior of SCC are slump flow diameter test, slump flow time test, V-funnel test, J-ring test, and L-box

Table 2 Different types and use of PET in SCC composites

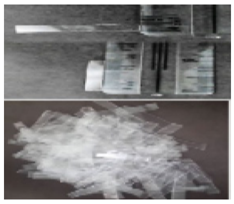
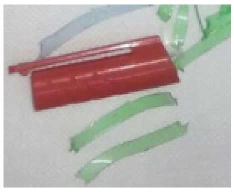
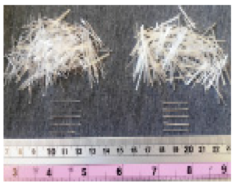
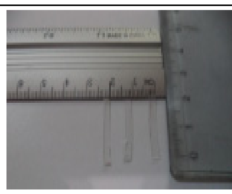
References	Type of SCC	Type of PET plastic	PET content	Particle size (thickness× width×length)	Measured hardened properties	Measured fresh properties	Shape
As'ad *et al*. (2011)	SCC	PET as fiber	0.5%, 0.1% and 1.5% of vol.	0.25 × 2 × 25 mm	--	slump, V-funnel, J-ring, U-box, and L-box tests.	
Kohistani and Singh (2018)	SCC	PET as FA	0.5, 0.75, 1, and 1.25 by wt.%	1-4 mm	$f_c' = 30$ MPa, split tensile and flexural strengths	slump, V-funnel, U-box tests.	
Khan and Ayub (2020)	R-SCC	PET as fiber & strips	1%	0.8 × 10 × 50 and strip 1900 mm long × 10 mm width	$f_c' = 30$ MPa, and flexural behavior of beams	----	
Ayub *et al*. (2021)	SCC	PET as fiber	2% by vol. fraction	0.8 × 5 × 25 mm	f_c'30 MPa, flexural strength, and tensile strength	slump, V-funnel, and L-box tests.	
Sadrmomtazi and Tahmouresi (2017)	SCC	PET fibers	0.2, 0.3, 0.4% by vol.	0.2 × 3 × 40 mm	E_C and $f_c' = 40$ MPa, split tensile, and flexural strengths	slump, V-funnel, T_{50cm}, and L-box tests.	
Madandoust *et al*. (2014)	SCC	PET as fibers	3, 4, 5 Kg/m^3	0.5 × 2 × 35 mm	Shrinkage and $f_c' = 30$ MPa, flexural strength, and tensile strength	slump, V-funnel, T_{50cm}, and L-box tests.	
Al-Hadithi *et al*. (2019)	SCC	PET as fibers	(0.25%, 0.5%, 0.75%, 1%, 1.25%, 1.5%, 1.75%, and 2%)	0.3 × 4 × 35 mm	Impact resistance and $f_c' = 40$ MPa and flexural strength	slump, V-Funnel, and L-box tests.	
Ganaw *et al*. (2018)	SCC	PET as fibers	0.05, 0.075, 0.1 and 0.125 of the cement weight	20 mm length	$f_c' = 30$ Mpa and flexural strength	slump, T_{50cm}, and J-Ring test.	
Al-Hadithi and Hilal (2016)	SCC	PET as fibers	0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2% by vol.	0.3 × 2 × 10 mm	$f_c' = 40$ Mpa and flexural strength	slump, V-funnel, wet density, and L-box tests.	

Table 2 Contined

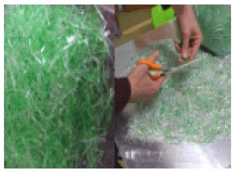
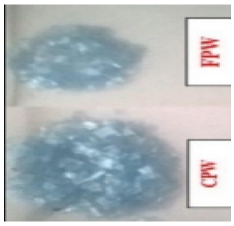
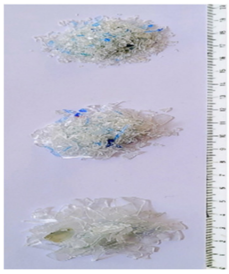
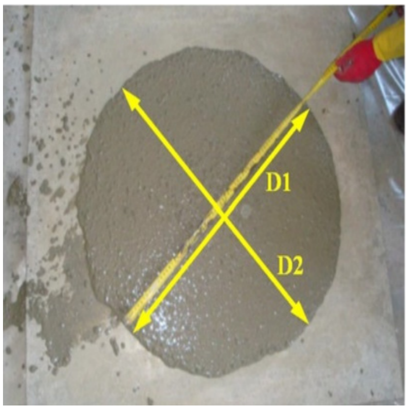
References	Type of SCC	Type of PET plastic	PET content	Particle size (thickness× width×length)	Measured hardened properties	Measured fresh properties	Shape
Burhan Al-Deen Abdul Rahman (2016)	R-SCC	PET as fibers	0.1%, 0.25% and 0.4%	0.2 × 2 × 25 mm	Load vs. deflection, toughness, $f_c' = 50$ Mpa, and the splitting test	slump, T_{50cm}, V-Funnel, and L-Box tests.	
Safi *et al.* (2013)	SCMs	PET as FA	10%, 20%, 30%, and 50% by wt. of sand	15-5 mm size distribution	The ultrasonic pulse velocity, $f_c' = 30$ Mpa	flow testing standard	
Mohammed *et al*. (2019)	SCC	PET as FA	0%, 2%, 4%, 6% and 8% by vol. of sand	< 4.75 mm	$\mathbf{f_c}' = 70$ Mpa	slump and $\mathbf{T_{50cm}}$ tests.	
Al-Hadithi and Frhaan (2017)	SCC	PPET as fibers	(0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2)% by vol.	0.3 × 4 × 35 mm	ultrasonic pulse velocity test, $\mathbf{E_C}$, $\mathbf{f_c}' = 50$ Mpa and flexural strength,	slump, V-funnel, and L-box tests.	
Hama and Hilal (2017)	SCC	PET as FA	0, 2.5, 5, 7.5, 10, and 12.5% by wt. of sand	1 mm & 4 mm	$\mathbf{f_c}' = 60$ MPa	slump, $\mathbf{T_{50cm}}$, V-Funnel, and L-box tests.	
Basser *et al*. (2022)	SCC	PET as FA	0,4, 8, 12, and 16% by wt. of sand	3 mm thick.	Stress-strain curve, $\mathbf{f_c}'$, flexural strength, and tensile strength	slump, $\mathbf{T_{50cm}}$, V-Funnel, and L-box tests.	
Aswatama *et al*. (2018)	SCC	PET as FA	0, 2.5, 5, 7.5, and 10% by the volume of sand.	----	$\mathbf{E_C}$, $\mathbf{f_c}' = 60$ MPa and splitting tensile strength	slump, L-shaped box, and V-Funnel tests.	
Oghabi and Khoshvatan (2020)	SCC	PET as fiber	0, 0.1, 0.25, 0.5, and 1 kg/m^3	0.02 × 1.83 × 10, 0.02 × 1.83 × 20, 0.02 × 1.83 × 30	$\mathbf{f_c}' = 50$ MPa and splitting tensile strength	slump, L-box and sieve segregation tests.	

Table 2 Continued

References	Type of SCC	Type of PET plastic	PET content	Particle size (thickness× width×length)	Measured hardened properties	Measured fresh properties	Shape
Sadrmomtazi *et al*. (2016)	SCC	PET as FA	5%, 10%, and 15% by the weight of sand	< 4.75 mm	$\mathbf{E_C}$ and $\mathbf{f_c}' = 40$ MPa, tensile and flexural strengths	slump, L-box test, and V-Funnel tests.	
Hasan-Ghasemi and Nematzadeh (2021)	SCC	PET as FA	0%, 5%, 10%, and 15% by the weight of sand	Maximum size = 6 mm	$\mathbf{f_c}' = 50$ MPa and splitting strengths, failure strain, $\mathbf{E_C}$, toughness.	slump, $\mathbf{T_{50cm}}$, L-box, and V-Funnel tests.	
Jaskowska-Lemańska *et al*. (2022)	SCC	PET as FA	0%, 5%, 10%, 15%, and 20% by the weight of sand	< 2 mm, 2- 4 mm and > 4	$\mathbf{f_c}' = 65$ MPa, splitting tensile strengths, $\mathbf{E_C}$, and poisson ratio	slump, $\mathbf{T_{50cm}}$, L-box, and V-Funnel tests.	

*Note: R-SCC: reinforced self-compacting concrete, SCMs: self-compacting mortars, FA: fine aggregate, **EC**: Modulus of Elasticity, **fc** ′: compressive strength, T_{50cm}: slump flow time



(a) Slump flow test

(b) V-funnel test

(c) J-ring test

(d) L-box test

Fig. 2 Instrumentation for assessing the fresh properties of SCC (Yang *et al*. 2015, Al-Oran *et al*. 2022) test. Past studies are reviewed and discussed to assess the influence of reinforcing PET waste fiber and PET waste aggregate on several fresh characteristics of SCC.

For the slump test, as illustrated in Fig. 2(a), the cone and the steel plate are utilized to address the flow ability of SCC in unconfined conditions. The larger diameter of the slump refers to better flowability of the SCC and the smaller diameter of the slump refers to less flowability of the SCC. Additionally, further information on segregation resistance may be acquired by measuring slump flow time (T_{50cm}) and lower time which refers to higher flowability. The value of slump flow test and T_{50cm} test, which satisfy the standard, is 650 - 800 mm and 2-5 seconds, respectively (EFNARC 2005).

For the V-funnel test, the V-shaped funnel tools, as shown in Fig. 2(b) is used to measure the filling ability of the SCC mixtures. The value of the v-funnel time that satisfies the standard is between 8-12 seconds (EFNARC 2005).

For the J-ring test, as shown in Fig. 2(c), the steel ring tools is used to assess the passing ability of the SCC mixtures. According to EFNARC (2005), the differences in height should be within 0-10 mm.

For the L-box test, as shown in Fig. 2(d), the rectangular steel L-shaped tools are utilized to assess the passing ability and flow ability of the SCC mixtures. According to EFNARC (2005), the blocking ratio must be at least 0.75 and the test must be completed within 5 minutes.

7. Fresh properties of SCC incorporating PET as aggregate and fiber

7.1 Slump flow and slump flow time (T_{50cm}) test

7.1.1 Impact of PET as aggregate

The impact of PET as an aggregate replacement on the fresh properties of SCC has been assessed and mentioned in many investigations (Safi *et al*. 2013, Sadrmomtazi *et al*. 2016, Hama and Hilal 2017, Aswatama *et al*. 2018, Kohistani and Singh 2018, Al-Hadithi *et al*. 2019, Hasan-Ghasemi and Nematzadeh 2021, Jaskowska-Lemańska *et al*. 2022). They found conflicting results about slump flow diameter of SCC under the impact of PET as aggregates replacement as shown in Fig. 3; a systematic reduction in diameter of slump flow have found due to increasing the content of PET aggregate. In the study performed by Hama and Hilal (2017), three various types of PET aggregates such as fine PET waste (FPETW) (passing through a 1 mm sieve), coarse PET waste (CPETW) (passing through a 4 mm sieve and retained on a 1 mm sieve), and mixed PET waste (MPETW) (40% of FPETW and 60% of CPETW) have been used as a replacement of fine aggregate. The authors found that by increasing PET aggregate from 0% to 12.5% with the interval of 2.5% in the SCC the slump diameter decreased gradually, as shown in Fig. 3. Moreover, the SCC containing CPETW type had the lowest slump flow diameter at each replacement level. Similarly, Basser *et al*. (2022) demonstrated that by introducing PET percentages as a replacement of sand, the slump value was reduced significantly. Investigators found that by increasing PET substitution to more than 10%, the slump value reduces to 400 mm. This is because SCC flows by its weight, reducing the unit weight of the mixes, and subsequently reducing its dispersion. Additionally, increasing the PET substitution level raises internal friction, which eliminates the motion of the coarse aggregate. In contrast to the earlier findings, some study indicates that increasing the PET ratio increases the slump flow diameter (Safi *et al*. 2013, Hasan-Ghasemi and Nematzadeh 2021). (Aswatama *et al*. 2018) conducted a study to observe the impact of adding PET as a replacement of sand on the fresh and mechanical performance of SCC mixture. According to their results, introducing PET aggregate enhances the workability of SCC mixture. Referring to Fig. 3, the greater slump flow diameter can be achieved by higher PET content. Beyond 10% PET content, the maximum slump flow diameter of the mixture can be achieved which is 815 mm without segregation or bleeding. These results are consistent with the findings of Safi *et al*. (2013). They were incorporated waste PET as sand replacement in a self-compacting mortar (SCM) mixing at different percentages of 0%, 10%, 20%, 30%, 40%, and 50% by weight. They found that adding the plastic particles improves the mini-

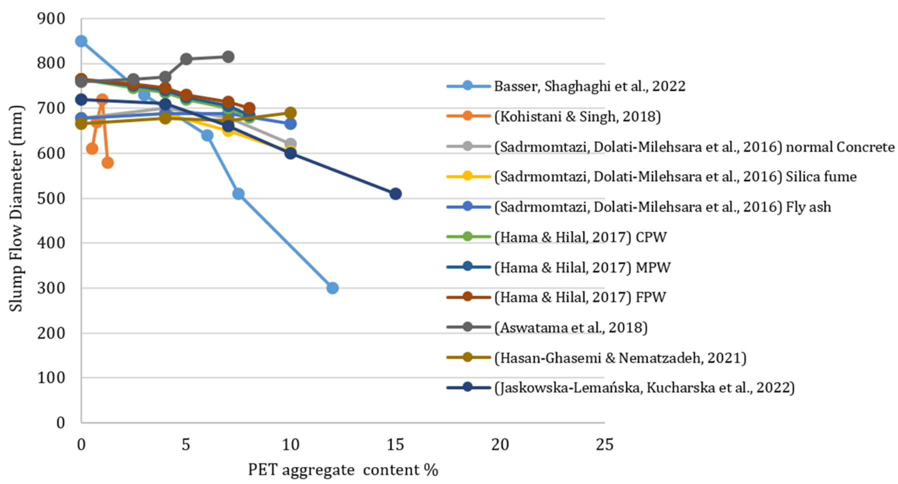


Fig. 3 Impact of PET waste particles as replacement of fine aggregate on the slump flow diameter test of SCC

slump value significantly. On the other side, many researchers were studied the slump flow time (T_{50cm}) (Hama and Hilal 2017, Aswatama *et al*. 2018, Hasan-Ghasemi *et al*. 2022, Jaskowska-Lemańska *et al*. 2022) as can be found in Fig. 4. (Hama and Hilal 2017) found that for the mix having a higher ratio of waste PET; the flow time was higher at all three types of plastic. Similarly, Basser *et al*. (2022) concluded that there is a direct correlation between PET percentage, as a replacement of fine aggregate, and T_{50cm}. In addition, Basser *et al*. (2022) found that by increasing the PET to 16 %, the slump flow declines to 400 mm and then T_{50cm} increases to 6.21 sec. On the other hand, Aswatama *et al*. (2018) demonstrated that the T_{50cm} was dramatically reduced with the increasing PET content of SCC mixture. T_{50cm} test illustrated that the fastest time is 5 seconds to reach 500 mm diameter using 10% of PET content and the longest time is 10.6 seconds with using 0% of PET content.

7.1.2 Impact of PET as fibe

The inclusion of PET fibers into SCC is usually caused a decline in slump test and an increase in T_{50cm} as shown in Figs. 5 and 6, respectively. Several past studies: (As'ad *et al*. 2011, Madandoust *et al*. 2014, Al-Hadithi and Hilal 2016, Al-Hadithi and Frhaan 2017, Ganaw *et al*. 2018, Al-Hadithi *et al*. 2019, Khan and Ayub 2020, Oghabi and Khoshvatan 2020, Ayub *et al*. 2021) discovered the loss in slump test of SCC mixtures incorporated PET fibers. For example, (As'ad *et al*. 2011) detected a decline in the diameter of slump test of SCC containing PET waste fibers. They noticed that an increment in the fiber percentages at constant water to cement ratio and super-plasticizer dosage constrained the flowing of the SCC owing to the interlocking of fiber and aggregates. At the same time, (Al-Hadithi and Hilal 2016, Al-Hadithi and Frhaan 2017, Sadrmomtazi and Tahmouresi 2017) investigated that irrespective of declined slump flow, still PET fiber mixtures may fulfill the specification of the standard (EFNARC 2005) for SCC. Further, Ganaw *et al*. (2018) stated that overall of the PETSCC mixes in their study are within the SCC range specified via EFNARC standards, and a 4.7% reduction in the slump test was noticed while 0.125% PET fiber content was employed. This could be because of the high surface area of PET waste fiber when incorporated into the mix. Furthermore, Ghorpade and Rao (2018) published similar findings, stating that the adding waste PET fiber in

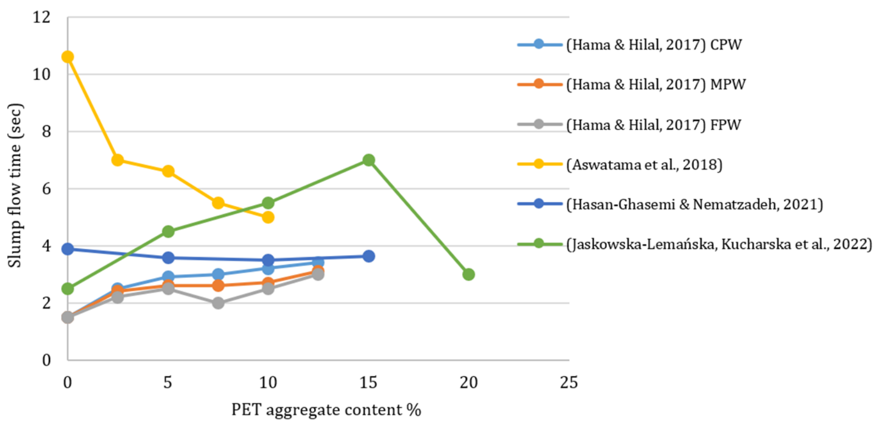


Fig. 4 Impact of PET waste particles as replacement of fine aggregate on the flow time ($\mathbf{T_{50cm}}$) test of SCC

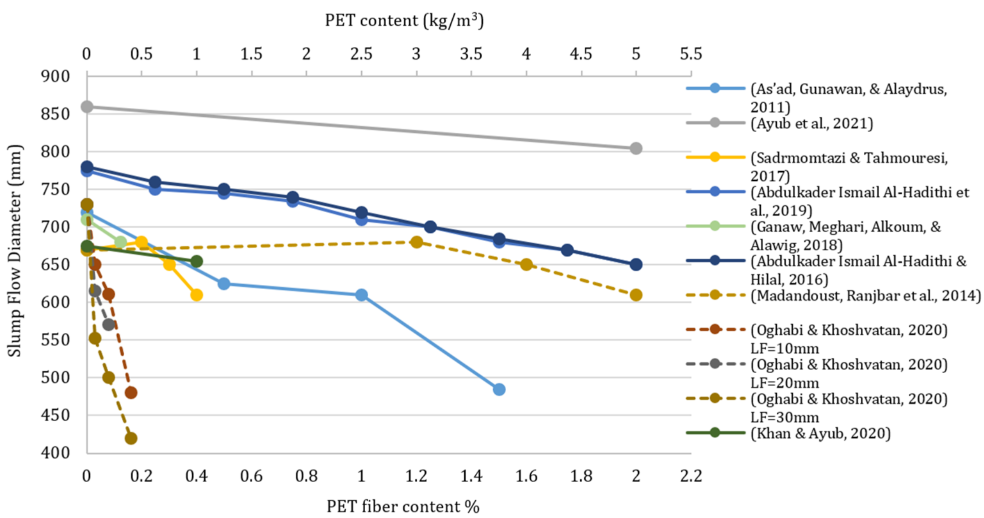


Fig. 5 Impact of PET waste fiber on the slump flow diameter of SCC
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

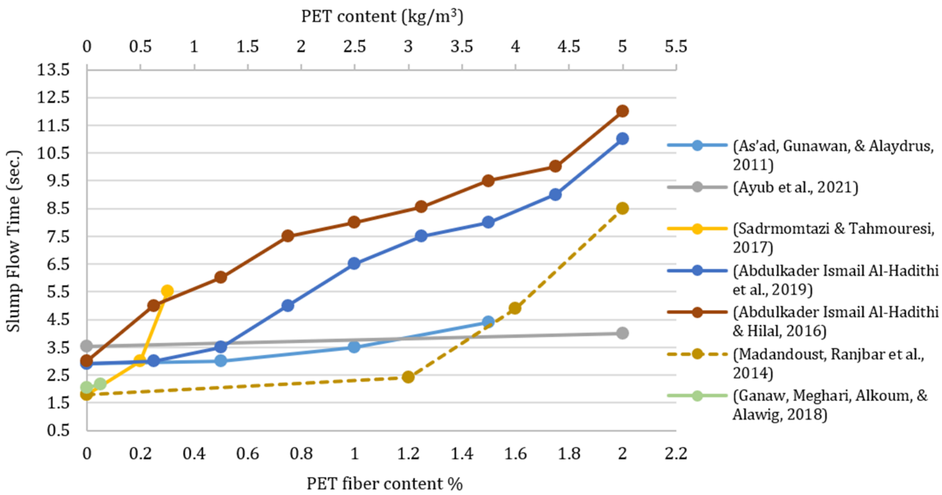


Fig. 6 Impact of PET waste fibers on the slump flow time $(\mathbf{T_{50cm}})$ of SCC.
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

7.2 V-funnel flow time

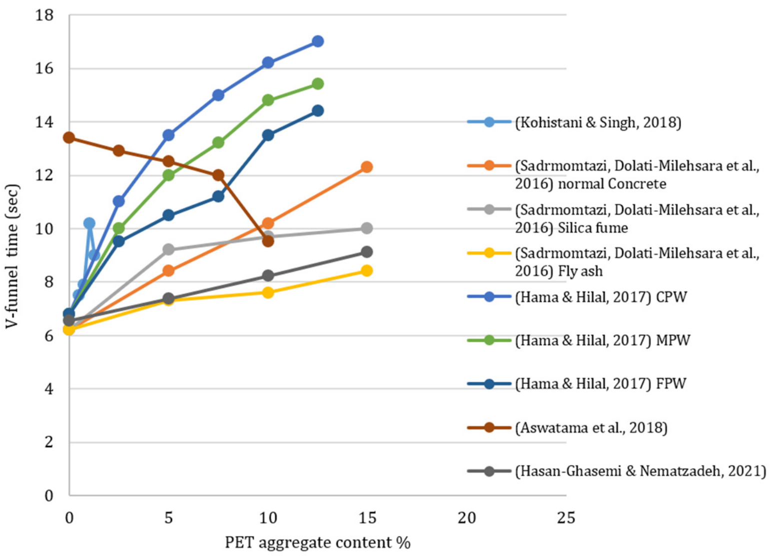


Fig. 7 Impact of PET waste particles as replacement of fine aggregate on the V-funnel time of SCC

SCC reduces slump flow and increases T_{50cm}. They adjusted the dosage of super-plasticizer to get an optimum content of plastic fiber which was up to 1%. However, for an extra increment in the waste PET fiber amount from 1.1% to 1.4%, they raised the percentage of reactive powders in the SCC mixtures to achieve good flow characteristics. According to their assessment, the addition of PET fiber content up to 1.4% had an impact on the flow characteristics in regard to reduced slump flow and increased T_{50cm}, while still remaining within the specified limit (EFNARC 2005). Another study carried out by (Al-Hadithi *et al*. 2019) utilized PET fibers in SCC mixtures and noticed a reduction in a slump at increasing PET content. Further, Khan and Ayub (2020) continued their research and used 1% PET fiber to explore the fresh properties of SCC. It was found that the flowability is within the recommended limits (EFNARC 2005) and that slump decreased up to 2.96% at 1% of PET fiber content.

7.2.1 Impact of PET as aggregate

V-Funnel flow test is commonly performed to measure the viscosity and flowability of the SCC. The viscosity of SCC can be investigated via both V-funnel time and T_{50cm}. As illustrated in Fig. 7, different outcomes were detected in the literature. the majority of studies (Sadrmomtazi *et al*. 2016, Hama and Hilal 2017, Kohistani and Singh 2018, Hasan-Ghasemi and Nematzadeh 2021) displayed that increasing PET waste aggregate will systematically increase the V-funnel time. For example, a study was carried out by Hama and Hilal (2017) to determine the impact of plastic waste on the workability of SCC. Investigators stated that as the amount of PET aggregate increased, the V-funnel flow time increased gradually. Similarly, Sadrmomtazi *et al*. (2016) documented a rise in the V-funnel flow time of SCC as the PET waste ratio increased from 5 to 15 weight percent (wt.%). In contrast to the earlier results, fewer studies stated that the V-funnel flow times of SCC decrease as the PET aggregate content increases (Aswatama *et al*.

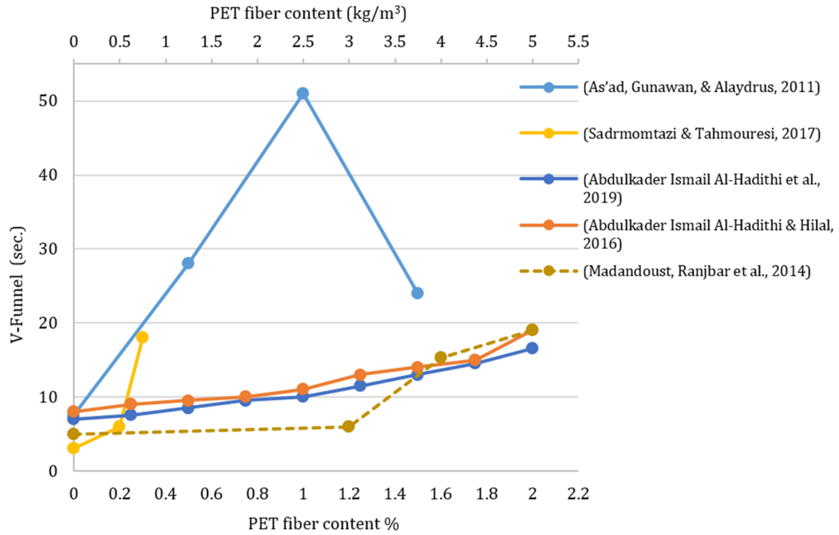


Fig. 8 Impact of PET waste fibers on the V-funnel time of SCC.
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

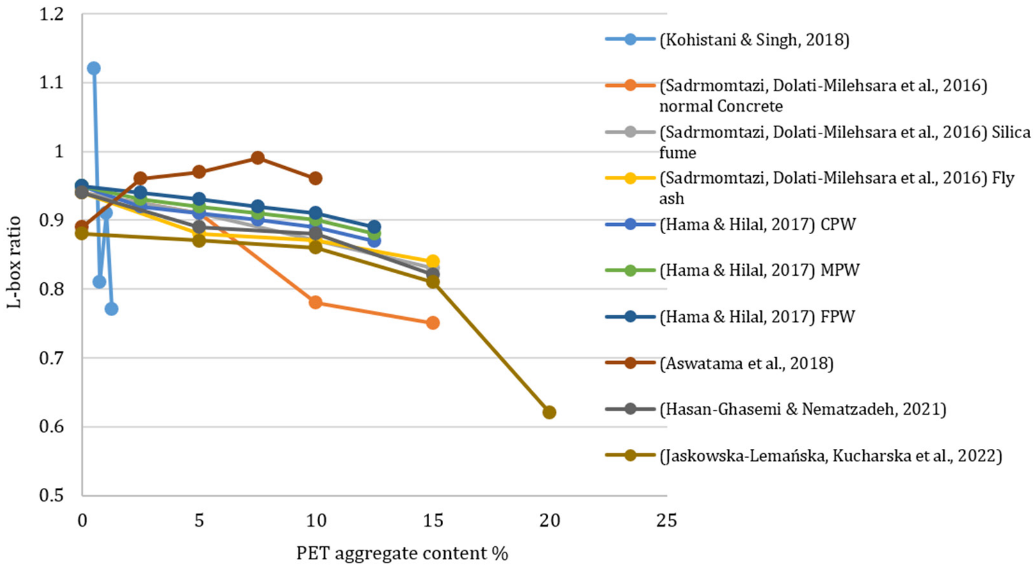


Fig. 9 Impact of PET waste particles as replacement of fine aggregate on the L-box ratio of SCC

2018).

7.2.2 Impact of PET as fiber

One of the most frequent problems in SCC is segregation, which mostly impacts coarse aggregates and increases the water content of concrete. The segregation assessed through V -Funnel test where coarse aggregate size may not pass 20 mm. Ozawa (1989) utilized V -Funnel test to assess the flow ability and segregation resistance of SCC. The utilization of PET waste fiber has a substantial influence on the filling ability of SCC. According to earlier research, as shown in Fig. 8, the amount of PET Fiber increases the V-funnel flow time considerably (As'ad *et al.* 2011, Madandoust *et al.* 2014, Al-Hadithi and Hilal 2016, Sadrmomtazi and Tahmouresi 2017, Al-Hadithi *et al.* 2019). Al-Hadithi and Hilal (2016) found that increasing the volume of PET fiber content from 0% to 2% resulted in an increase in the V-funnel flow time from 9 seconds to 25 seconds. The same outcomes were also gained in another research conducted by Al-Hadithi *et al.* (2019). which utilized different percentage of plastic fibers from 0.25% to 2% with the interval of 0.25% in the SCC. They determined that by introducing PET fiber in SCC the V-funnel flow time was increased from 7 to 16.5 seconds. However, negligible influences on measured V-funnel time were noticed with using a smaller amount of PET fibers (0.5-0.75%). Still, beyond 1% PET fibers content, the calculated V-funnel time remained with the range of EFNARC specifications. Similarly, Madandoust *et al.* (2014) observed the impact of PET waste fibers on the filling ability of SCC by inserting various PET waste fiber amounts (0, 3, 4 and 5 kg/m^3). Moreover, they discovered that raising the PET fiber percentage can reduce filling ability of SCC. At 5 kg/m^3 of PET content, the V-funnel time was raised from

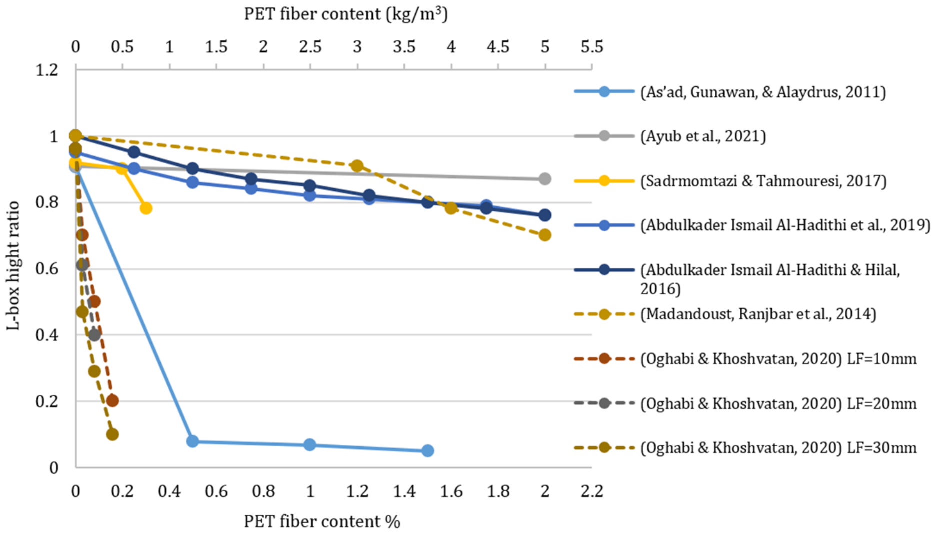


Fig. 10 Impact of PET waste fibers on the L-box ratio of SCC
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

5 to 19 seconds. Further, Sadrmomtazi and Tahmouresi (2017) observed that the V-funnel time of all mixes containing PET fiber was gradually increased with the increment of PET fiber. The time increased by 50% and 83% for the mix containing 0.2% and 0.3% of the PET fiber content, respectively, compared to the reference mix; but the mix containing 0.4% PET fiber resulted in the immobility of the mixture in a confined environment. However, according to As'ad *et al.* (2011) the lowest v-funnel time was obtained by incorporating 1.5% of PET fiber in SCC which is equal to 24 s compared to 0.5% and 1% of PET fiber in SCC is 28 s and 51 s, respectively. According to the authors, the higher weight of the mixture with 1.5% of PET fiber content was higher on gravity force, which caused it to fall faster out of the V-funnel base gate.

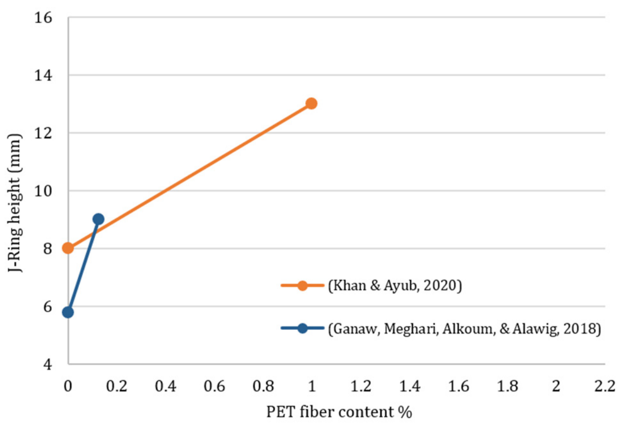


Fig. 11 Impact of PET waste fibers on the J-ring height of SCC

7.3 L-Box

7.3.1 Impact of PET as aggregate

The L-Box test is usually performed to evaluate the passing ability of the SCC. As shown in Fig. 9, the value of L-box height ratio dramatically reduced with the increase of the partial substitution of PET aggregate content (Sadrmomtazi *et al.* 2016, Hama and Hilal 2017, Hasan-Ghasemi and Nematzadeh 2021, Jaskowska-Lemańska *et al.* 2022). Sadrmomtazi *et al.* (2016) stated that increasing the PET aggregate amount from 0% to 15% caused a change in the L-box blocking ratio of SCC including PET from 0.95 to 0.75. As illustrated in Fig. 9, SCC with 5% PET aggregates created the highest blocking ratio, while SCC with 15% PET aggregates led to the lowest ratio. The shape of PET aggregates has a crucial role in achieving such behavior. Further, Jaskowska-Lemańska *et al.* (2022) found that SCC with a 15% PET substitution did not fulfill the criteria of SCC for passing ability; beyond 4 cm length of plastic bag waste fiber (PBWF) led to immovability of SCC mixes and decrease the passing ability of SCC.

7.3.2 Impact of PET as fiber

The L-box test can be utilized to check the passing ability of the SCC through narrow openings and without segregation or blockage among reinforcing bars. The values of the L-box blocking ratio were significantly reduced by increasing PET Fiber contents, as illustrated in Fig. 10. This indicates that the capability of fresh SCC to pass into dense reinforcement has reduced (As'ad *et al.* 2011, Madandoust *et al.* 2014, Al-Hadithi and Hilal 2016, Sadrmomtazi and Tahmouresi 2017, Al-Hadithi *et al.* 2019, Oghabi and Khoshvatan 2020, Ayub *et al.* 2021). As'ad *et al.* (2011) were detected that almost all SCC mixtures with PET fibers did not agree with the specifications of SCC that needs at least H2/H1 ratio of 0.8. only SCC with 0% plastic fibers recorded a suitable ratio of 0.905. Madandoust *et al.* (2014) experimentally studied the effect of different quantities, 0, 3, 4, and 5 kg/m^3, of PET fibers on the various properties of SCC. The results showed that 3 kg/m^3 PET waste fibers can be regarded as acceptable content for fresh and hardened characteristics of SCC. Al-Hadithi *et al.* (2019) showed that the low flow velocity and the addition of waste

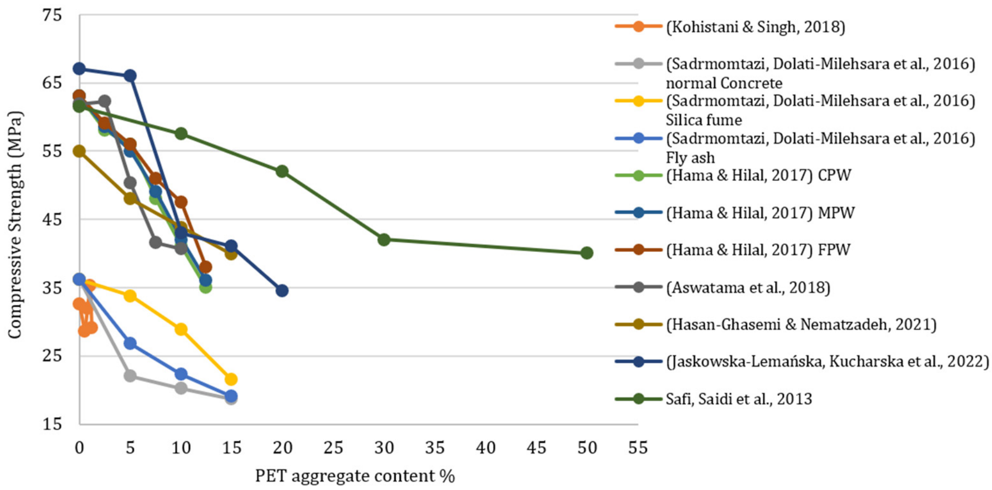


Fig. 12 Impact of PET waste aggregates as replacement of fine aggregate on the Compressive Strength (MPa) of SCC

PET fibers to the SCC mixes resulted in a reduction in the ratio of H2/H1. This was due to the higher viscosity of mixes including waste PET fibers as a result of fibers inhibiting flow. Oghabi and Khoshvatan (2020) checked the effect of different quantities (i.e., 0.1, 0.25, 0.5, and 1 kg/m^3) and lengths (i.e., 1, 2, and 3 cm) of PET fiber on the passing ability of SCC. They observed that as the length of the PET fiber increased, the passing ability of SCC through rebar significantly decreased. Sadrmomtazi and Tahmouresi (2017) noticed that increasing PET fiber amount from 0% to 0.3% led to a decrease in the blocking ratio of SCC including PET from 0.92 to 0.78. In the same vein, Ayub *et al*. (2021) stated that increasing PET fiber amount from 0% to 2% led to a drop in the blocking ratio of SCC including PET from 0.91 to 0.87, as revealed in Fig. 10.

7.4 j-ring test

7.4.1 Impact of PET as aggregate

J-ring tests can be used with slump flow tests to determine whether self-compacting concrete is able to pass through steel bars (Hwang *et al*. 2006). The difference between the concrete height outside and inside the ring is known as the J-Ring height (ΔH). For the SCC incorporating recycled plastic, the value of ΔH should be less than 50 mm in order to achieve adequate flow through the rebar (Hwang *et al*. 2006). Interestingly the study conducted by Safi *et al*. (2013), Sadrmomtazi *et al*. (2016), Hama and Hilal (2017), Kohistani and Singh (2018), Al-Hadithi *et al*. (2019), Hasan-Ghasemi and Nematzadeh (2021), Jaskowska-Lemańska *et al*. (2022), no one has measured the J-ring test of SCC incorporating PET aggregate as replacement of fine aggregate.

7.4.2 Impact of PET as fiber

The incorporation of PET fiber decreased the passing ability in J-ring test of SCC, as demonstrated in Fig. 11. (Ganaw *et al*. 2018, Khan and Ayub 2020) found that the addition of PET fiber in SCC mixtures resulted in a small increase in the height of the J-ring test. They observed that the increasing PET waste fiber dosage from 0% to 0.125% led to the change in the height of the J-ring of SCC from 5.8 mm to 9 mm, respectively. This was a result of fiber which can cause particle clogging during flow. Khan and Ayub (2020) also found that there is an increase in the height value of J-ring for SCC incorporating PET waste fiber. The authors mentioned that raising the PET waste fiber percentage from 0% to 1% increased the J-ring height from 8 mm to 13 mm.

8. Mechanical properties of SCC incorporating PET as aggregate and fiber

8.1 Compressive strength

8.1.1 PET as aggregate

Compressive strength is the most crucial parameter which validates concrete performance. The 28 days' compressive strength results of SCC, contains various percentages of PET aggregate, reported in the literature and demonstrated in Fig. 12. The produced compressive strength was ranged from 30 to 70 MPa referring to the past investigations (Sadrmomtazi *et al*. 2016, Hama and Hilal 2017, Aswatama *et al*. 2018, Kohistani and Singh 2018, Hasan-Ghasemi and Nematzadeh 2021). This figure shows that all studies indicate that the compressive capacity of SCC declines with increasing the PET aggregate content. The percentage of strength reduction was based on the utilization of PET aggregate content. According to Sadrmomtazi *et al*. (2016), adding 15% PET aggregates caused about 48.3% reduction in compressive strength, also stated that the decrease in the compressive strength of concrete incorporating silica fume was lower than fly ash and normal cement. Hama and Hilal (2017) observed a systematic reduction in the compressive strength of SCC containing PET waste aggregates as a substitution for sand. It was found that replacing 12.5% of the sand with waste PET aggregate leads to a decline in the compressive capacity to 45% of the reference samples. While 2.5% of PET aggregate caused a decrease in the compressive capacity of 8%. The main reason for the reduction in

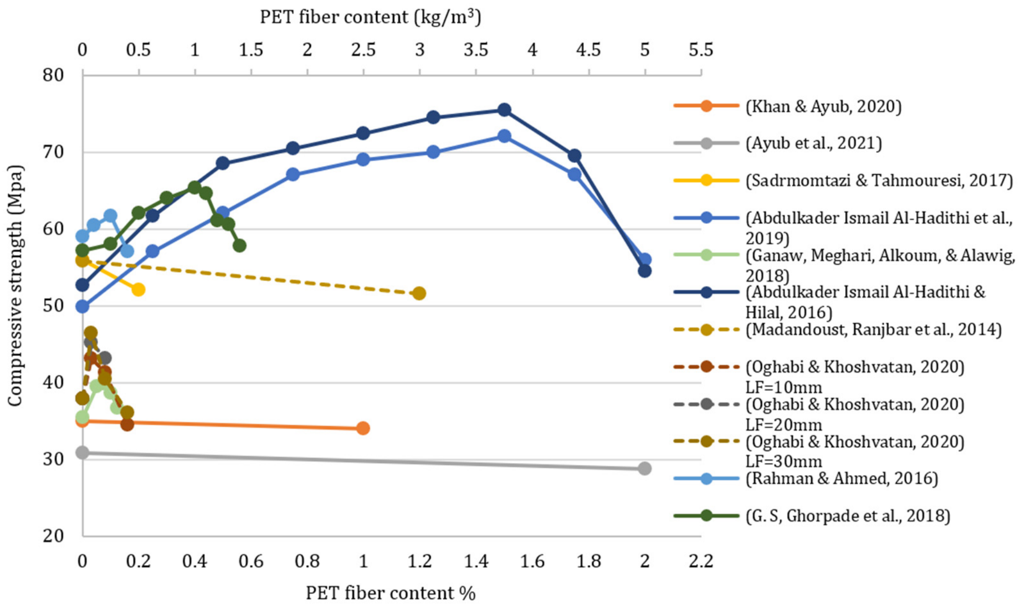


Fig. 13 Impact of PET fiber content on the Compressive Strength (MPa) of SCC
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

strength with the increasing of PET particles is the bond among the PET and the cement paste matrix, which is easily deteriorated by the incorporation of PET aggregates (Sadrmomtazi *et al*. 2016). Since the PET aggregate is softer than the natural aggregate, in which during the loading stage, PET aggregates works as voids through the matrix, which causes cracks to form around the particles.

8.1.2 Impact of PET as fibers

Generally, concrete is good for compressive strength. While it is weak in tensile strength. Thus, fibers are added to concrete to enhance tensile strength and, as a result, increase compressive strength. Using PET Fiber greatly influences the compressive strength of SCC, as shown in Fig. 13. The literature showed that the compressive strength of SCC increases with the increment of PET fiber contents up to a specific limit (Madandoust *et al*. 2014, Al-Hadithi and Hilal 2016, Sadrmomtazi and Tahmouresi 2017, Ganaw *et al*. 2018, Ghorpade and Rao 2018, Al-Hadithi *et al*. 2019, Khan and Ayub 2020, Oghabi and Khoshvatan 2020, Ayub *et al*. 2021). Based on the findings of Al-Hadithi and Hilal (2016) and Al-Hadithi *et al*. (2019), the compressive strength of SCC was enhanced by the increment in the PET fiber percentages up to 1.5%, and then the effect was reversed as shown in Fig. 13. Oghabi and Khoshvatan (2020) assessed the optimum dosage for incorporating plastic bag fiber in SCC. They stated that the maximum compressive and tensile strength were achieved by incorporating 0.25% of PET fiber with a length of 3 cm into self-consolidating concrete. Irrespective of the fiber length, the tensile strength of PETSCC declined with increasing fiber content of more than0.25% (Oghabi and Khoshvatan 2020).

In contrast to the outcomes mentioned earlier, some studies indicated that the increase in the PET waste fiber (PETWF) ratio declines the compressive strength of PET-SCC (Madandoust *et al*. 2014, Sadrmomtazi and Tahmouresi 2017, Khan and Ayub 2020, Ayub *et al*. 2021). For example, Ayub *et al*. (2021) discovered that increasing the PETWF content from 0 to 2%, of SCC's volume, decreases the compressive strength of the SCC by about 6.85%. The reason for this degradation could be related to the excessive paste demand due to the addition of larger volume PET fiber.

8.2 Splitting tensile and flexural strength

8.2.1 PET as aggregate

The tensile and flexural strength of the SCC was reduced with the introduction of PET aggregate. Fig. 14 displays the records of the tensile strength of PETSCC gained in earlier studies. For example, Sadrmomtazi *et al*. (2016) noticed a decrease in the tensile strength of SCC containing three different PWA contents of 5%, 10%, and 15%. Similarly, (Hasan-Ghasemi and Nematzadeh 2021) conductedan experimental study to find the effect of various plastic waste aggregate contents on SCC performance. The tensile capacity was found to decrease systematically via the increment of plastic waste aggregate ratio. Furthermore, (Aswatama *et al*. 2018) performed experimental research to investigate the impact of different plastic waste aggregate amounts on the behavior of SCC. As shown in Fig. 14, the tensile strength was found to reduce with the addition of PET aggregate content up to 5%, and beyond that increase in the tensile strength was also reported.

The flexural strength of SCC containing plastic waste aggregate follows the same pattern of tensile strength, as can be observed in Fig. 15, which presents the results from previous experiments (Safi *et al*. 2013, Sadrmomtazi *et al*. 2016, Kohistani and Singh 2018). The flexural strength of PETSCC is decreased as a result of the inclusion of plastic waste aggregate in SCC. For example, Sadrmomtazi *et al*.

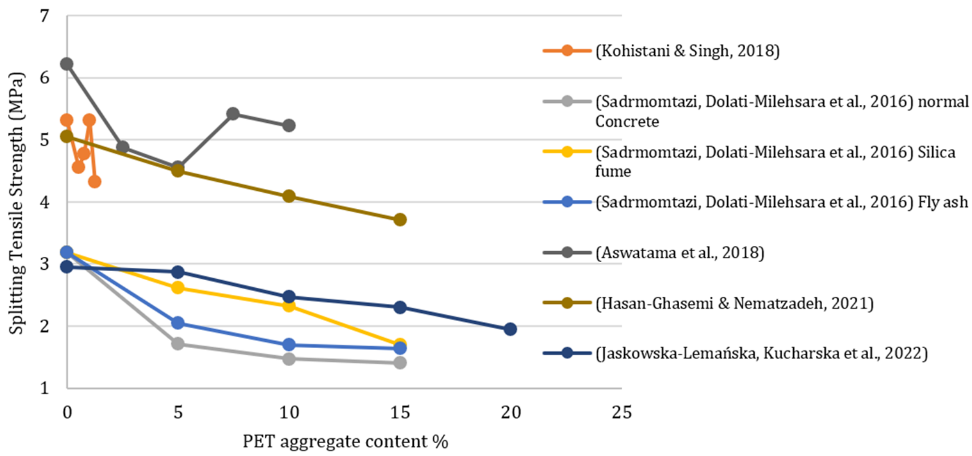


Fig. 14 Impact of PET waste aggregate content on the Splitting Tensile Strength (MPa) of SCC

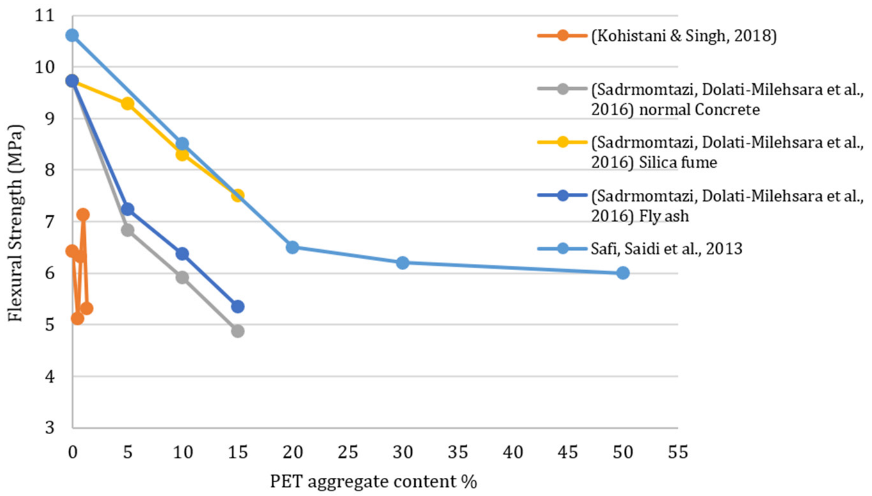


Fig. 15 Impact of PET waste aggregate content on the Flexural Strength (MPa) of SCC

(2016) discovered that increasing the plastic waste aggregate content in SCC mixtures reduced its flexural strength. Moreover, their results revealed that the influence of silica fume and fly ash in PETSCC mixtures enhances the flexural strength of concrete containing PET aggregates. In the same manner, another research given by Safi *et al.* (2013) was carried out on the mechanical characteristics of self-compacting mortars (SCMs) continuing PET waste as fine aggregates. They used four different plastic aggregate content, 0%,10%, 20%, 30%, and 50%. It was seen that the flexural strength of SCMs decreased with an increase in plastic aggregate content at all curing ages. This is because of the low resistance of the PET waste aggregate (Choi *et al.* 2005, Rai *et al.* 2012, Safi *et al.* 2013). Furthermore, Kohistani and Singh (2018) found that using of 1% plastic waste as a fine aggregate and 10% Alccofine as a cement in SCC mixtures improves the flexural strength of PETSCC.

8.2.2 PET as fiber

For normal concrete and SCC, crack development and propagation during loading is one of the main complications. The use of PET fiber helped to tackle this issue and worked as a link to minimize the development of cracks. Fig. 16 displays the relation between SCC's tensile capacity and different PET fiber contents, the results show that the tensile capacity of SCC increases with increasing PET fiber contents, as mentioned in the earlier studies (Madandoust *et al.* 2014, Abdul Rahman 2016, Sadrmomtazi and Tahmouresi 2017, Oghabi and Khoshvatan 2020, Ayub *et al.* 2021). Most investigations found that the adding PET fiber to PETSCC enhanced its tensile strength. For example, Madandoust *et al.* (2014) stated that the splitting tensile strength of PETSCC improved from 3.57 MPa to 3.82 MPa by raising the PET fiber amount from 0 kg/m^3 to 3 kg/m^3. Similarly, Ayub *et al.* (2021) confirmed that the tensile strength of PETSCC was enhanced by adding 2% volume fraction of PET fiber. Furthermore, Oghabi and Khoshvatan (2020) evaluated the impact of different length and contents of fiber on the tensile strength of PETSCC. They observed that all samples of PETSCC increased in tensile capacity, with the exception of a sample that contains 1 kg/m^3 fiber.

The flexural Strength of SCC is also improved with the increasing of PET fiber content up to specific limit, as shown in Fig. 17, which presents the results from previous experiments (Madandoust *et al.* 2014, Al-Hadithi and Hilal

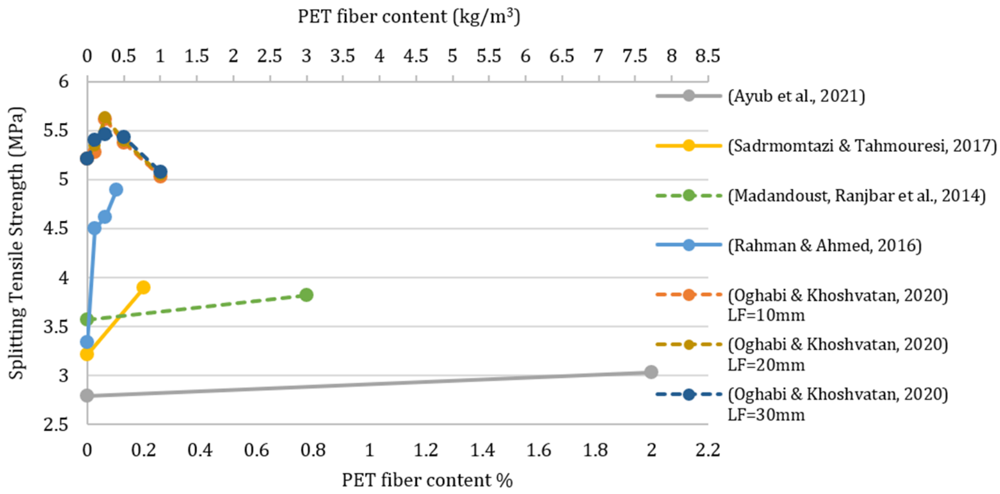


Fig. 16 Impact of PET fiber content on the Splitting Tensile Strength (MPa) of SCC.
Note: [Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

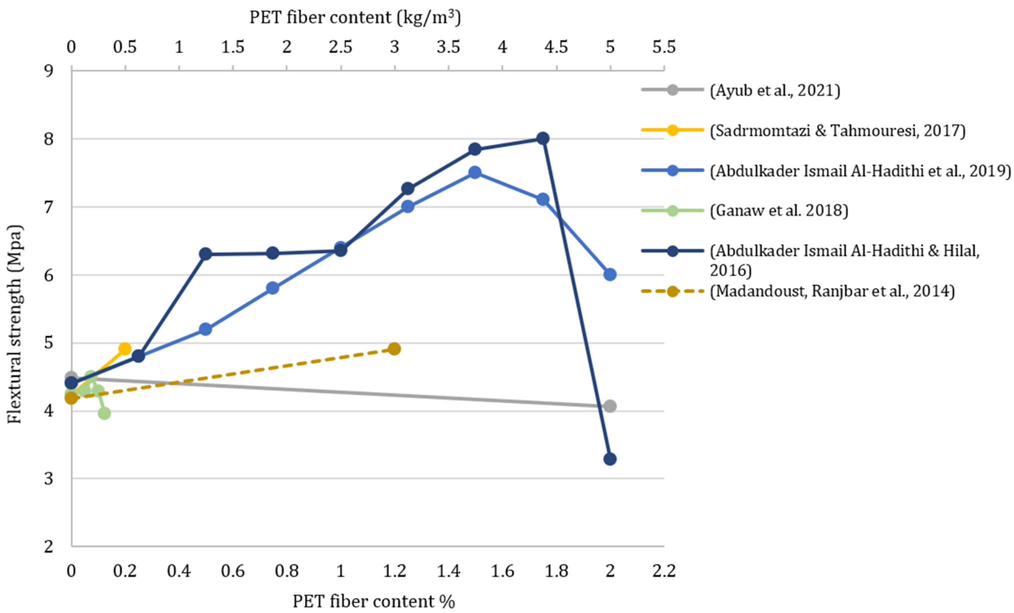


Fig. 17 Impact of PET fiber content on the flexural Strength (MPa) of SCC.
[Solid lines indicate the substitution rate by volume; dotted lines indicate the substitution rate by weight]

2016, Sadrmomtazi and Tahmouresi 2017, Ganaw *et al*. 2018, Al-Hadithi *et al*. 2019, Ayub *et al*. 2021). Al-Hadithi *et al*. (2019) proved that the flexural strength tended to be improved via increasing PET fiber content up to 1.5% by volume. Beyond this content, the flexural strength declined due to the irregular distribution of PET waste fiber. Nonetheless, strength's values were higher than that for control samples (i.e., without PET fiber). Similarly, an increase in flexural strength of SCC containing PET fiber was observed in (Madandoust *et al*. 2014, Sadrmomtazi and Tahmouresi 2017). Contrary, Ayub *et al*. (2021) found that the flexural strength of SCC incorporating 2% PET fiber was 9.5% lower than that of reference samples.

8.3 Modulus of elasticity (E_C)

8.3.1 PET as aggregate

The modulus of elasticity (E_C) is an important property of concrete structures, and it has a direct relation to the strain resistance of the concrete. The outcomes of E_C of SCC containing different percentages of PET aggregate for the past studies are demonstrated in Fig. 18; where the obtained modulus of elasticity was measured to be ranged from 12-38 GPa (Sadrmomtazi *et al*. 2016, Aswatama *et al*. 2018, Hasan-Ghasemi and Nematzadeh 2021, Jaskowska-Lemańska *et al*. 2022). For example, Sadrmomtazi *et al*. (2016) concluded that the modulus of elasticity of SCC containing PET aggregates as substitution of sand in different concrete mixtures such as, normal concrete, concrete with silica fume and concrete with fly ash were

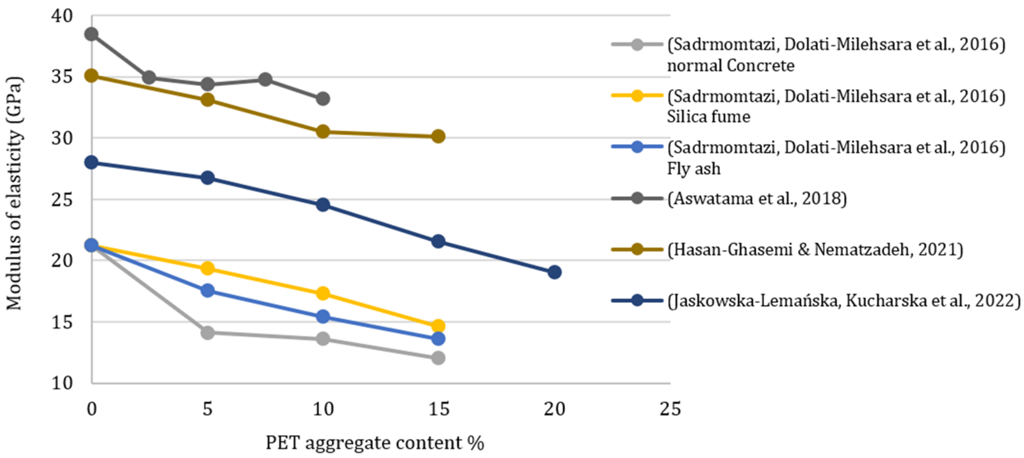


Fig. 18 Impact of waste PET aggregate content on the Modulus of elasticity (Gpa) of SCC

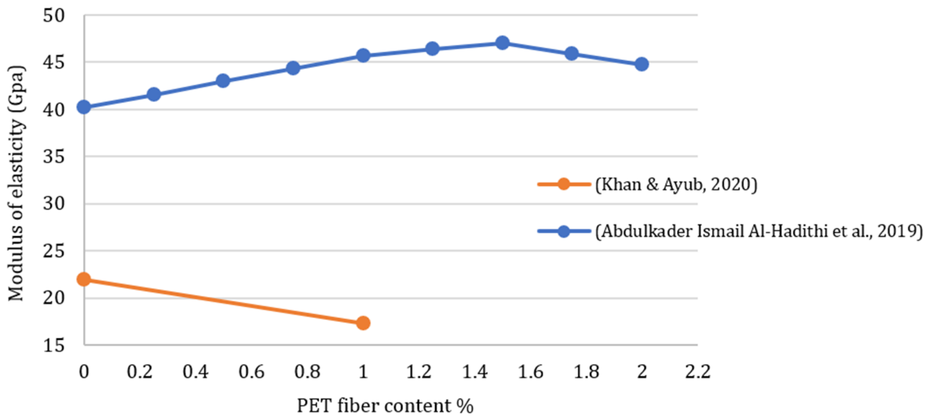


Fig. 19 Impact of PET fiber content on the Modulus of elasticity (GPa) of SCC

decreased. However, their results revealed that the influence of silica fume and fly ash in PETSCCA enhances E_C of samples containing PET aggregates. Similar results on E_C decrease with increasing PET aggregates content were found by Aswatama *et al.* (2018), Hasan-Ghasemi and Nematzadeh (2021), Jaskowska-Lemańska *et al.* (2022). The main reason for the decrease in E_C of PETSCC is the replacement of high $E_C$fine aggregates with very low E_C soft PET aggregate.

8.3.2 PET as fibers

The incorporation of waste PET fiber in SCC has different effects on the modulus of elasticity of SCC as shown in Fig. 19. Al-Hadithi *et al.* (2019), Khan and Ayub (2020). Al-Hadithi *et al.* (2019) concluded that increasing the fiber content from 0% to 2% would improve 11% of the modulus of elasticity, while a slight improvement has been noticed beyond 1.5% of fiber content. Conversely, Khan and Ayub (2020) examined the effect of introducing with 1% volume of PET fibers into the SCC, which resulted in a 21% decrease in the modulus of elasticity compared with the reference sample.

9. Discussions

Through an extensive literature review on SCC mix design methods and the impact of waste PET fiber and waste PET aggregate reinforcement on various properties of SCC, the following discussions were made:

I. Empirical mix design, despite its simplicity, requires more experimental testing in order to determine the appropriate behavior of constituent materials and the most appropriate mix ratios. On the other hand, the compressive strength mix design method offers a precise and uncomplicated approach for achieving desired component quantities, reducing the need for trial mixes. However, a limitation of this method is that it requires adjustments to the proportions of all self-consolidating concrete (SCC) components to attain an ideal mix percentage. The statistical factorial mix design method simplifies the testing process for adjusting self-compacting concrete, optimizing stability, flow, deformability, and strength. However, it demands substantial raw material testing for correlation establishment. In contrast, the rheology paste design offers desired workability with less lab work, especially for fiber-reinforced SCC with various properties and steel fiber options. It also allows for SCC incorporating pure limestone powder without cement. The Close aggregate packing mix design is simple with less binder use but prone to SCC segregation, a common construction issue. In eco-SCC design, obtaining desired concrete durability is challenging due to a high water-to-powder ratio and limited cement substitution. Precise additive levels are crucial. The close aggregate packing design is recommended for achieving desired concrete properties, including strength and workability.

II. Production of PET aggregate and fiber can be achieved through two main methods including Direct Mechanical Recycling, this involves shredding plastic in a shredding machine and manual cutting. It is cost-effective and efficient for research purposes. Direct Melting and Shaping method, in this approach, waste PET bottles are melted and configured into specific sizes and shapes. This method yields materials with more consistent sizes and properties.

III. The impact of adding PET aggregate to Self-Compacting Concrete (SCC) on the slump test varies. Generally, it negatively affects the slump test, although conflicting findings exist. Smooth, rounded PET aggregate, especially at low substitution levels (<15% by volume), can improve the slump test. However, rough, flattened PET aggregate can restrain fresh concrete flow. PET fiber addition leads to decreased slump diameter and increased T_{50cm} due to fiber clustering, reducing workability. Chemical additives like superplasticizers, viscosity modifiers, and mineral additives can enhance PETSCC's slump flow properties regardless of the mix composition.

IV. The partial replacement of sand with PET aggregate content in SCC adversely impacts the outcome of V-Funnel time testing; it increases with the increase of PET aggregate contents. However, some authors found different results. This is because of the smooth surface of this type of plastic, which lead to staying together and adversely affect SCC's fresh properties. Whereas SCC containing PET aggregate with spherical shape can decrease the V-Funnel time. However, the V-funnel flow time considerably increases with increasing PET fiber content.

V. Adding PET aggregate to SCC as a replacement for fine aggregates reduces the value of the L-box height ratio. This reduction could be due to the flat surface of PET particles that can stick together and make it difficult to pass the fresh PETSCC between the rebar of the L-box device. In contrast, in some investigations, the addition of PET aggregates improved the passing ability of concrete in regard to the l-box height ratio. This is due to the initial hypothesis in which the smooth surface of plastic helps other materials flow more easily on fresh concrete. On the other hand, the L-box blocking ratio values significantly decreased with increasing PET Fiber contents.

VI. The inclusion of PET fibers negatively impacted the mixtures, resulting in increased J-ring height values. This is primarily due to fiber-induced particle clogging during the flow.

VII. The addition of PET aggregates in SCC has led to a systematic reduction in compressive strength. Furthermore, using coarse plastic waste reduced SCC's compressive strength more than fine plastic waste. The main reason for the decrease is the bond between the PET and the cement paste matrix, which easily deteriorates by incorporating PET aggregates. On the other hand, PET fiber contents up to specific limits have a positive impact as it remarkably enhances the compressive strength of SCC.

VIII. The incorporation of PET aggregate in SCC consistently decreased its tensile and flexural strengths, similar to the effect observed on compressive strength. Conversely, the presence of PET fibers in SCC reduced crack development and propagation during loading, leading to enhanced tensile and flexural strength in SCC.

IX. Introducing PET aggregate instead of sand in the SCC reduces its Young's modulus. At the same time, using silica fume and fly ash in PETSCC improves the elastic modulus of a mix containing PET aggregates. In contrast, adding PET fibers enhances the strain rate of SCC and increases the elastic modulus.

10. Conclusions

1. The incorporation of PET plastic waste into SCC influences the rheological and mechanical characteristics of the concrete, which must be considered before use for construction. The general conclusions of this review study are as follows:
2. The process of melting and incinerating waste plastic results in the release of various chemicals and hazardous pollutants into the atmosphere. Conversely, incorporating waste plastic into construction practices presents a safer and more environmentally friendly alternative. Additionally, the utilization of waste plastic in construction offers economic advantages over the use of conventional additives, aggregates, and other components found in cementitious materials.
3. Designing the mix for Self-Compacting Concrete (SCC) is a complex task, and none of the discussed mix design methods fully satisfy all objectives and criteria. Some methods perform better in durability and sustainability, while others are better suited for technical aspects of SCC. Therefore, the model or method for developing SCC must be selected based on the requirements and application. Combining different models makes it possible to ensure characteristics in future research and meet a wide range of needs.

4. Increasing the amount of PET plastic in the SCC mix diminishes the workability of the fresh characteristics, but at the same time enhances the hardened characteristics of the SCC.
5. SCC with acceptable fresh and mechanical properties could be produced by using PET plastic fiber.
6. In the literature, most studies have replaced fine aggregate with PET aggregate. Fewer studies have focused on replacing PET plastic with coarse aggregate. This is primarily because substituting fine aggregate yields improved mechanical and fresh properties in concrete.
7. The mechanical and fresh properties of PETSCC are largely influenced by the size, shape, and amount of PET plastic.
8. Reducing a building's self-weight helps reduce the building's seismic risk, since seismic forces are linearly related to self-weight.
9. The fresh characteristics of PETSCC can be enhanced by adding PET Plastic particles which have a smooth and slippery surface.

Future research directions

This review paper confirms that PET plastic waste can be used to create low-cost and environmentally friendly Self-Compacting Concrete (SCC). It highlights the fresh and mechanical properties of SCC with PET plastics. However, further research is necessary to explore hardened properties such as bond strength, thermal characteristics, and resistance to abrasion and impact. Additionally, more studies on substituting PET plastic for coarse aggregate are needed to assess its practicality and economic feasibility.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data analyzed during this study are included in current manuscript.

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