

Application of Recycled Steel Fibre in Malaysia: A Review

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Abstract. The amount of waste tyres is expected to increase with the surge of vehicle ownership in Malaysia as tyres are vehicle vital components that require regular replacement. The improper disposal of waste tyres has generated environmental issues. Energy recovery through burning, recycling, and disposal in legal and illegal landfills are common methods in disposing of waste tyres in Malaysia. Studies show that waste tyres contain steel fibre that can be extracted and has the potential to be used in construction. In Malaysia, existing methods of material recovery are shredding and pyrolysis. The steel retrieved from waste tyres exhibits good adhesion with mechanical strength recorded up to 2165 MPa and a modulus of 300. However, the uneven shape, length, and geometry can lead to a balling effect when incorporated into concrete but with a proper mix proportion this issue can be managed. Addition of recycled steel fibre to concrete can enhance its structural strength and crack-bridging effect while the use of recycled steel fibre in hot mix asphalt can enhance its tensile strength and toughness. The utilisation of steel recovered from waste tyres presents an opportunity to address environmental concerns related to waste tyre disposal and its potential applications.

1 Introduction

Car ownership has shown a major increase in the recent year. As of the year 2021, the Ministry of Transportation Malaysia has reported a total of 33 million registered vehicles in Malaysia [1]. Tyres are required to be replaced after reaching their end of life. Due to the increased production and sales of vehicles, a significant quantity of waste tyres is expected to be generated [2]. The disposal of old tyres has raised concerns over the environment and public health, and studies have been done on the appropriate methods for their disposal [3]. The Malaysian Association of Tyre Retreaders & Dealers Societies (MATRDS) has addressed the issue of tyre dealers in Malaysia facing the problem of managing waste tyres due to recycling factories refusing them while the authorities ban the disposal of waste tyres in landfills without providing alternative solutions [4]. In Sabah, stern actions have been taken by the authorities for the illegal disposal of this material as it would create a breeding

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ground for mosquitoes [5]. This situation indirectly emphasises the need for viable methods of recycling waste tyres. The objective of this paper is to assess the method of extracting steel components from tyres and reusing these steels as construction materials while addressing the environmental difficulties associated with tyre disposal. The paper will highlight the existing tyre waste management practices, assess the mechanical and structural properties of recycled steel fibres extracted from waste tyres, and examine the potential applications of these fibres in enhancing the feasibility of recycling tyres.

2 Overview of waste tyre disposal issue

Tyre is one component of a vehicle that requires regular replacement after they reach their useful life. This is to ensure the safety of the vehicle user. A study has shown that 37% of car accidents in Malaysia that involve tyre issues has resulted more than three fatalities for a single accident [6]. The process of replacing a worn out tyre generates waste that requires proper disposal. This has posed an alarming environmental and health issue in the recent year as it is reported that 54% of Malaysian household own more than one car [7].

2.1 Magnitude of the problem

In the year 2021, the automotive industry consumes around 65% of the total global production of both natural and synthetic rubbers with the worldwide tyre market recorded at a total of 2268 million units in 2021, and it is projected to grow to 2665 million units by the year 2027 [8]. This rapid growth comes with a significant problem of how to properly handle the disposal of discarded tyres and approximately 1.5 billion tyres are discarded annually, posing a global challenge in terms of waste tyre management due to the lack of coordinated processing or existing recycling framework [3]. Landfilling may have been the most economical method as the treatment facilities for this waste is inadequate [9]. This issue emphasises the urgent requirement for sustainable and efficient methods to tackle the environmental consequences and resource issues related to their disposal.

2.2 Environmental hazard

The improper disposal of tyres is a significant environmental risk, since waste tyres emit toxic substances into the soil and water. In a study by Turner and Rice in 2010, they found that waste rubber tyres can release hazardous and poisonous substances, such as manganese and iron, into the nearby ecosystem. With the usage of zinc as a vulcanization activator in tyres, and it is noted that zinc leachate is the primary contributor to the toxicity in the surrounding environment particularly concerning in areas near landfills and other waste sites where there is a large accumulation of discarded tyres [3].

2.3 Landfill concern

The disposal of discarded tyres in landfills is generally acknowledged as one of the most harmful ways of tyre disposal, to the point that it is officially forbidden in the European Union [10]. The magnitude of the environmental hazards linked to this practice becomes evident when tyres, owing to their considerable size and volume, occupy extensive amounts of space in landfills. This not only reduces the landfill's ability to handle other forms of garbage, but also worsens by slow decomposition rate of non-biodegradable tyre components in the landfill [8].

2.4 Fire hazard

Stockpiles of discarded tyres pose a significant risk of fire hazard during dry seasons since the flames are challenging to put out. This is due to the tyres high energy content and the ample oxygen supply in the wide empty spaces. Efforts to put out tyre fires using water also pose a concern by transferring hazardous byproducts into the environment [11]. The growing quantity of waste tyres poses a significant danger to the environment and human well-being and illegally discarded or accumulated tyres provide a risk of unregulated combustion and the release of dangerous substances such as sulfur oxides and polycyclic aromatic hydrocarbons. For instance in 2016, 9000 people were evacuated in Spain due to the combustion of illegal waste tyre dump [12]. The act of storing tyres in landfills increases the risk of fires and leads to the emission of harmful smoke and pollutants such as zinc oxide and dioxins [8]. Tyre components possess a high degree of flammability and consequently, extinguishing these flames proves to be difficult, resulting in considerable harm, compromised air quality, and the emission of poisonous chemicals. Ultimately, this leads to reduced visibility in the vicinity [3].

2.5 Economic implication

The processing and refining of waste tyres especially using pyrolysis technology involve costly expenditure, including initial investment and continuous servicing [13]. Due to expensive cost linked to the processing of products derived from waste tyres, 90% of reclaimed waste tyres are exported to countries with more affordable labour and less strict environmental regulations. Furthermore, waste tyre processing is made more difficult by the collection fees, which restricts the profits to be used to compensate recyclers for the expenses associated with tyre processing. Moreover, the increased expenses associated with transportation to reach the processing plant serve as an additional obstacle to the processing of waste tyres [3]. Although the material recovered from waste tyre have been widely studied and discussed in engineering application [9], the acceptance from the industry is still an obstacle regarding its quality and durability and awareness is required in order to break into the market [14].

2.6 Technological gaps

During the early 1990s, it was possible to recover tyre rubber using mechanical methods. However, the recycling process of waste tyres becoming more challenging after much more complicated formulas and additives are introduced to the tyre manufacturing [15]. The qualities of tyre recycled products are affected by the presence of impurities, requiring a major effort to remove non-rubber components during the recycling process [3]. Several devulcanization techniques, such as thermomechanical and mechanochemical methods, were attempted to reverse the process of vulcanization. While the use of this technology has resulted in a much improved final product, none of the current procedures have achieved complete devulcanization [15]. One of the challenges for the development of the recycling waste tyre is to optimise the use of this recycled material to form new product. By having a market need for the recycled material, the recycling industry will become much more viable [11].

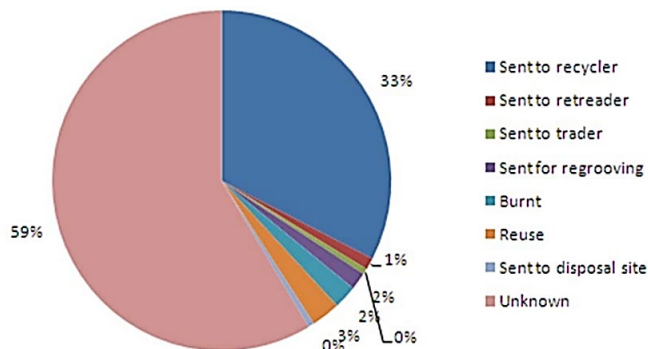


Fig. 2. Waste tyre disposal survey report [16]

Generally, there are few methods of disposal for waste tyre in Malaysia. Energy recovering as a supplementary fuel for cement kiln is one of them. However, it is important to consider that the burning of scrap tyres is a breach with the Environment Quality Act. Tyre wastes are also recycled into a valuable resource called "tyre derived product" such as asphalt paving mixture and other rubber products through recycling, pyrolysis and reclaim treatment facilities. However due to the limited availability of facilities that provide this kind of treatment, the majority of these wastes tyre are disposed of in both legal and illegal landfills [7].

4 Recycling initiative for waste tyre

In addressing the environmental issue of waste tyre disposal, many methods have been implemented to reduce the negative impact and to find more sustainable waste management methods in dealing with tyre disposal. Figure 3 illustrates the waste tyre management procedures and their respective uses. Mechanical recycling is becoming a common method for recovering various resources, including rubber and steel. These resources may then be reused in industries such as rubber product manufacture, civil engineering, and geotechnical engineering. On the other hand, thermochemical conversion techniques such as gasification, combustion, and particularly pyrolysis, can generate various fuel types, such as oil, char, and syngas [2].

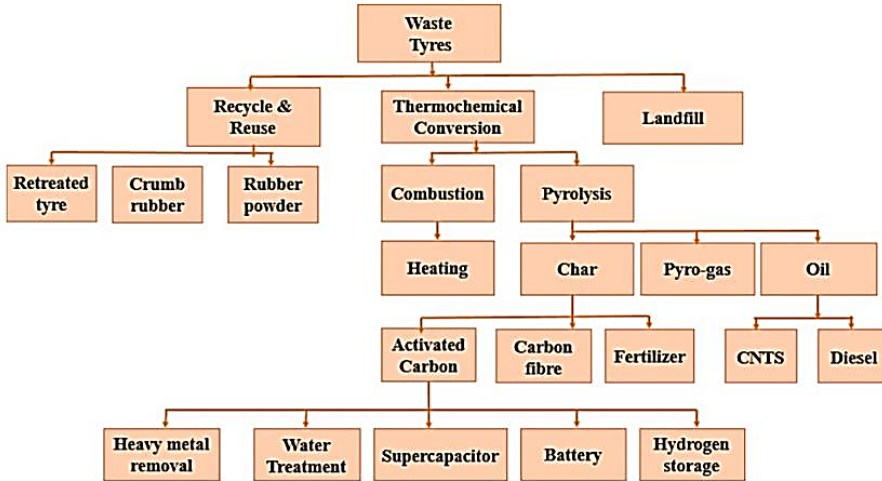


Fig. 3. Waste Tyre Management [2]

5 Retrieving steel fibres from waste tyre

Rubber is the main component of a tyre, which makes up around 70% to 80% of the tyre's mass along with steel belts and textile overlays. These components contribute to the tyre's final shape and functional qualities [13]. The tyre consists of a complex mix of materials, natural and synthetic rubber, fibre and steel wire making the tyre itself hardly resistant to biodegrade. Table 1 and Figure 4 show the tyre composition and typical components respectively. Tyres contain up to 15% to 25% of steel depending on the source of the vehicle [17]. The process of retrieving steel from a tyre is commonly done mechanically using shredding and anaerobic thermal degradation of the waste tyre using the pyrolysis procedure.

Table 1. Tyre composition [13]

Materials	In USA		In European Union	
	Passenger tyre	Truck tyre	Passenger tyre	Truck tyre
Natural rubber (%)	14	27	22	30
Synthetic rubber (%)	27	14	23	15
Carbon black (%)	28	28	28	20
Steel (%)	14–15	14–15	13	25
Fabric, fillers, accelerators, antiozonants, etc. (%)	16–17	16–17	14	10
Average weight	New 11 kg, Scrap 9 kg	New 54 kg, Scrap 45 kg	New 8,5 kg, Scrap 7 kg	New 65 kg, Scrap 56 kg

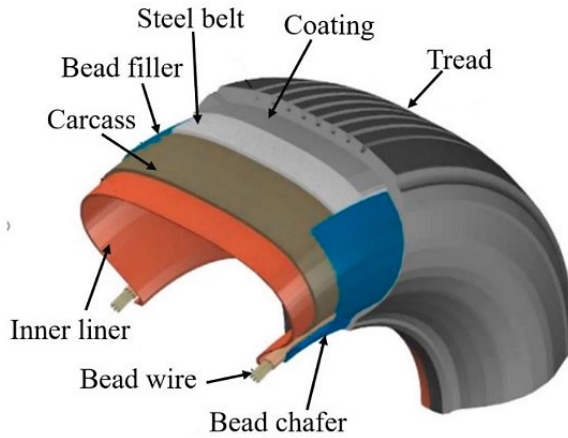


Fig. 4. Tyre typical component [11]

5.1 Shredding method

Tyre shredding is a procedure that involves a sequence of cutting and granulating tyres into rubber granulates of a desired size. Initially, the majority of reinforcing steel in waste tyres is removed by the bead extractor, where steel wires are pulled mechanically using a large hook [11]. A magnet is used to extract the steel from the rubber granules during the cutting and granulation process [11]. The process of retrieving steel fibre from waste tyres is shown in Figure 5. During the steel separation process, rubber mulch passes on a vibrating belt through electromagnets that pull in loose steel wires. Most steel fibres are already separated from the rubber due to previous grinding steps. Pieces with rubber still attached undergo further sorting and processing, such as vibration, pneumatic separation, or additional grinding. This process may be repeated to reach the desired level of purity [11]. Throughout the granulation process, the length of the steel will decrease. As a result, the steel that is obtained has an irregular length of steel fibres and still contains a small amount of rubber and fluff [17].

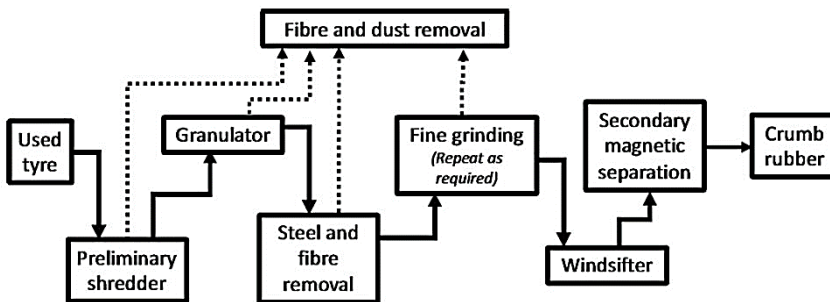


Fig. 5. Retrieving steel from waste tyre through shredding [11]

5.2 Pyrolysis method

Pyrolysis of tyres is where tyres are thermally decomposed, in the absence of oxygen, into their organic and inorganic components. The process is shown in Figure 6. The process produces hydrogen, methane, and other hydrocarbons, as well as oil and solid residues consisting of steel and low-grade carbon black [2]. Changing the heating temperature and time may change the end-product ratio. Within a normal pyrolysis facility, used tyres are placed into a pyrolysis reactor, where they are subjected to high temperatures until they reach the specified temperature. A gas-liquid separator process separates the extracted vapours into gases and liquids. Upon the end of the process, the steel is segregated from the char, although some of the steel still contains char on the surface. The char resulting from pyrolysis may have lower quality, making it challenging to market and thus impacts the economic viability of pyrolysis plants [17].

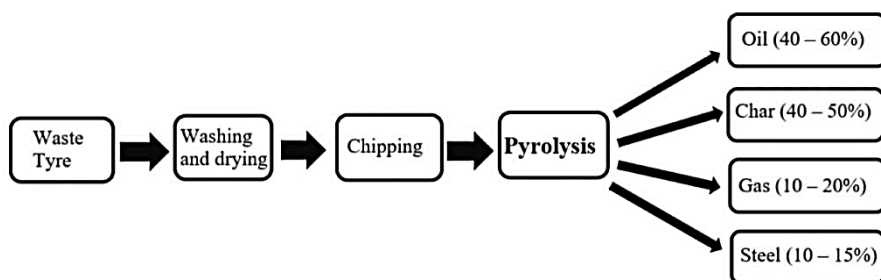


Fig. 6. Retrieving steel from waste tyre through pyrolysis [11]

6 Mechanical and structural properties of recycled steel fibres from waste tyre

According to ASTM A 820-01, the mechanical qualities of steel fibre are specified in terms of tensile strength. It is required that the average tensile strength of the steel fibre should be equal to or more than 345 MPa, while no individual sample shall have a tensile strength below 310 MPa. Meanwhile, it is indicated that the fibre must meet its bending criterion, which entails withstanding bending around a pin with a diameter of 3.18mm to an angle of 90 degrees at a temperature of no less than 16 °C without experiencing any breakage [18]. In a study of feasibility of recycled steel fibre retrieved from tyre incorporate with cementitious composite has identified that the recycled steel fibre used in this study come with a diameter of 0.22mm and density of 7800 kg/m³ and possessed up to 2165 MPa of tensile strength with the elastic modulus of 300 [19]. Another study found that a recycled steel fibre from tyre with diameter of 0.3mm have the tensile strength of 712.32 MPa and the elastic modulus value of 197.9 as shown in Table 2. In identifying the tensile strength, a tensometer was used to assess the tensile strength of the waste tyre fibres. Fibres were attached to both ends of the tensometer grips and a pulling load was applied. A graph was being produced until the loading process stopped after a fibre break. The maximum load was observed at the moment of failure. During this study, it is noted that the failure mode for waste tyre steel fibre reinforced concrete has relatively little brittleness compared to concrete without fibre where it exhibits sudden and explosive brittleness [20].

Table 2. Properties of waste tyre recycled fibre [20]

Property	Quantity
Diameter of twisted fibre (mm)	1.3
Diameter of individual tiny wires (mm)	0.3
Cross-sectional area (mm ²)	1.33
Fibre length (mm)	65
Aspect ratio	50
Tensile force (N)	945
Strain	0.0036
Tensile strength (MPa)	712.32
Elastic modulus (GPa)	197.9
Surface texture	Rough
Shape	Twisted cylindrical

7 Application of recycled steel fibre

Studies have been done to investigate the performance of utilising the recovered steel fibre from waste tyres in the concrete mix. Previous studies have found that an addition of a certain proportion of steel fibre from a waste tyre into concrete has been proven to enhance its mechanical properties such as compressive strength, flexural strength, tensile strength and toughness.

7.1 Concrete industry

While being a more economical and environmentally friendly method for the construction of reinforced concrete structures, the use of recycled tyre steel fibres as an alternative to manufactured steel fibre has the potential to enhance the properties of concrete [21]. A study was done on the effects of fatigue stress on concrete reinforced with a mixture of manufactured steel fibres and recycled steel fibres from waste tyres. The result of the study shows the mix of both types of fibre can endure up to five times higher displacement compared to plain concrete [22]. The aforementioned research combined provide significant insights into the use of recycled steel fibres derived from scrap tyres to enhance a range of mechanical qualities in concrete.

7.1.1 Effect of geometry and morphology of Recycled Steel Fibre on concrete

The geometry of steel fibre plays an important role in the performance of the mechanical strength of a concrete especially under tensile load. This includes the aspect ratio, shape and distribution of a fibre in a concrete mix. The aspect ratio can be defined as the ratio of fibre length to an equivalent fibre diameter, denoted as l/d [23]. The surface roughness of a fibre has implications on the performance of a fibre as the small diameter fibre will have a bigger surface area which it will increase the distribution within the concrete matrix but reduce the workability of the concrete in return [24]. A prior research was conducted to investigate the effect of roughness on the bonding ability of sanded steel fibre, which revealed an increase in bonding strength where a higher degree of roughness provides a greater contact area with the cement paste and this surface irregularity enables better packing of the small cement grain resulting a dense layer of hydrates can develop around the rough fibre [25]. Figure 7 shows

the morphology of recycled steel fibre. A study that performed a pull-out test to evaluate the adhesion of recycled steel fibres found that, although with their shorter length, demonstrate similar results to longer hooked manufactured steel fibres because of their excellent adhesion to the cement mortar. The study concludes that recycled tyre steel fibres, regardless of their thickness, demonstrate exceptional adhesion, hence improving the structural strength of concrete and its ability to bridge cracks. The crack-bridging effect helps in suppressing the propagation of micro-cracks, hence enhancing the cracking toughness of cement composites [26].

Aspect ratio has been proven to significantly impact the fibre balling effect of a concrete [27]. According to the American Concrete Institute (ACI) 544.3R-08, the most common aspect ratio of steel fibre preferably falls within the range of 30 to 100 with a length of 13mm to 64mm [28]. According to previous research, it has been shown that an increase in aspect ratio leads to a greater enhancement in strength. However, it can be difficult to get a homogeneous mixture when the aspect ratio exceeds 100 [29]. The reduction in the compressive strength of steel fibre reinforced concrete, when using a high dose and longer length of steel fibre, may be attributed to the decreased workability of the concrete mix. This leads to the formation of a weaker-quality matrix with undesirable holes and cavities [30]. A prior study has used the recycled fibre from waste tyre with 0.2mm diameter and 3.1mm to 15.6mm in length has proven that with 3% by volume, it can enhance the performance of the flowability and mechanical properties of a concrete. However it was noted that due to its shorter length of fibre with an average of 7.4mm, it reduces the strength anchorage bond in mitigating the propagation of the crack [31]. In a separate study, when a recycled steel fibre of 6mm to 19mm in length with a diameter of 0.22mm is partially replaced with a commercial steel fibre of 12mm in length and 0.039mm diameter, it can reduce the loss of fluidity due to its larger diameter however the further increase of recycled steel fibre has a negative effect on the tensile strain capacity. Due to its bigger diameter, it has reduced the amount of fibre with the same percentage which weaken the pullout strength in mitigating the microcracking. In this study, the optimum result is achieved by incorporating 1.75% of commercial steel fibre with 0.25% recycled steel fibre into engineered cementitious composite [19].

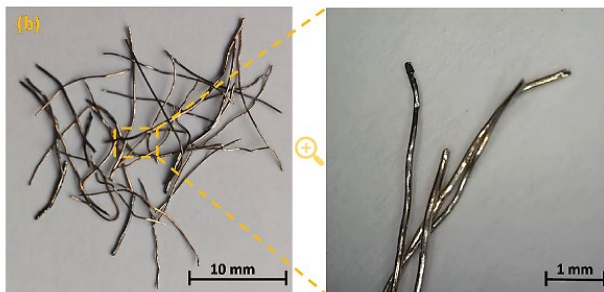


Fig. 7. Recycled tyre steel fibre morphology [19]

Several fibre shapes have been developed to enhance the crack-bridging capacity of fibres. The shape of fibres can be classified as a crimped, straight, spiral, hooked end, and twisted [32]. By introducing a hook end into fibres could significantly enhance the flexural strength and splitting tensile strength of concrete as a result of crack bridging action, post crack behaviour and the end shape of a fibre where it has the ability to increase the bonding between fibre and the concrete matrix. By a means of absorbing more energy, it influences the degree of toughness qualities of concrete. However, the steel fibre retrieved from a tyre may have a less uniform shape where it may contain different variations of geometry, shape

and length [33]. Figure 8 shows the typical shape of recycled steel fibre compared to the manufactured steel fibre in a study conducted by Michalik et al., 2023.

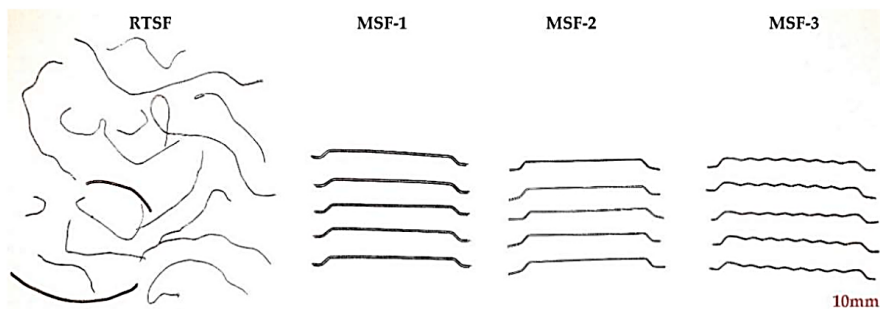


Fig. 8. Steel fibre various shapes [26]

7.1.2 Steel fibre proportioning in concrete mix

Achieving the correct volume percentage is crucial to maintaining the workability of the concrete, making it easier to place and compact. At the same time, it has a crucial function in increasing the toughness and ductility of the concrete, resulting in greater resistance against cracking and deformations as it hardened. The selected volume ratio has a significant role in preventing cracks from spreading and improving the long-lasting quality of the concrete by effectively bridging the cracks. ACI 544.3R-08 specification suggest that more than 2% by volume percentage (V_f) of these fibres in concrete may cause the potential of balling [28]. A previous study concluded that based on the fresh and hardened properties of concrete, it is recommended 2% as the optimum recycled steel fibre content where it increases the compressive strength up to 30% in a cubic sample, 25% of splitting tensile strength and 272% of flexural strength however this ratio is dependent on the water-cement ratio or the use of superplastizer [34]. A study on utilisation of recycle steel fibre in the self-compacting concrete conclude that the workability of fresh concrete is decreased with the increase in the volume fraction of fibre. However, the workability of the concrete was enhanced by using a polycarboxylate-based polymer plasticizer admixture, which also ensured a more uniform distribution of fibers within the mix. The research observed that an increase in the volume percentage of fibre resulted in improvements not only in compressive strength, but also in splitting tensile and flexural strength. However, it is important to address the issue of fibre balling for future investigation [35].

In the study that assessed the steel fibre's influence on key mechanical properties such as compressive strength, tensile strength, and toughness by comparing the factory-manufactured steel fibre with the tyre-recycled steel fibre shows that when the fibre volume ratio is same, the strength and flexural toughness of recycled steel fibre reinforced concrete tyres are lower compared to industrial steel fibre reinforced concrete. To achieve the same strengthening or toughening effect, the amount of tyre-recycled steel fibers needs to be approximately 1% to 2% higher compared to industrial steel fibers. [36]. A study that primarily aimed to optimise the length and dose of tyre-recycled steel fibres by conducting mechanical property tests when incorporated in concrete and observing their microstructure, revealed that 2.5% is the optimum dosage of steel contain by weight in concrete and 7.62cm length of fibre can enhance the flexural capacity of a concrete by 10% to 12% [30]. A comparative analysis shows the recycled steel fibre performance against other fibres often used in construction applications. It was discovered that recycled steel fiber can control drying shrinkage cracking

on the first day of curing, similarly to industrial polypropylene fiber, when used at the same volumetric content. This effectively reduces the occurrence of cracking [37].

7.2 Pavement and road construction

The study into the incorporation of steel fibre in hot mix asphalt also draws the attention of researchers, who believe that it is advantageous for enhancing the strength of asphalt hot mix [38]. A research on steel fibre-reinforced asphalt concrete was conducted to evaluate several factors of steel fibres, such as aspect ratio, section type, and roughness by evaluating the cracking resistance using an indirect tension test at low temperatures. The findings indicated that the tensile strength and toughness of asphalt concrete were enhanced with the use of longer fibres and fibres that were shorter than 6mm in length or had a diameter smaller than 0.01mm did not provide any reinforcing effects. It also noted that steel fibres with a length of 30mm and a diameter of 0.3mm demonstrated a remarkable 895% enhancement in toughness [39].

Previous research suggested that by incorporating waste fibres into asphalt mixtures it greatly improved their overall performance, leading to cost savings in the production process and environmental benefits. The study also indicates that fibre-reinforced asphalt mixtures in porous friction courses, exhibit improved performance in reducing binder drainage, enhancing tensile strength, minimising permanent deformation, and increasing resistance to moisture susceptibility [40]. To avoid potential issues like tyre puncture, it is recommended to use steel fibre in the binder course of a flexible pavement rather than the surface layer [41]. It is important to note that the steel fibres collected from discarded tyres come in different shapes and lengths, and may also include rubber contamination. These attributes influence the efficiency of this substance when integrated into hot mix asphalt [38].

8 Challenge and future direction

Several methods in retrieving the steel content from waste tyre include complex procedures, such as shredding and pyrolysis operations involving more complex design an operation with high initial investment cost when conducted on a laboratory scale[11], hence has been a challenge in adopting in industrial implementation. For this approach to be viable, market acceptance of the output material is crucial. The advancements in waste tyre recycling technologies offer a promising direction for further study, particularly in the areas of grinding and shredding of tyres [12].

Based on the studies that have been highlighted, there is potential of utilizing recycled steel fibre extracted from waste tyre. Not only can it improve the mechanical characteristics of cement composite, it also can be incorporated into hot mix asphalt with the potential of enhancing its properties. However, due to the limited facilities for extracting steel of waste tyres especially in Malaysia, the viability of processing waste tyre is yet to be fully explored. Through this finding, it can help to develop further interest in optimising the feasibility of extracting steel fibres from waste tyres, highlighting its potential impact on both the construction industry and environmental sustainability.

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