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Review Article

A comprehensive overview about recycling rubber as fine aggregate replacement in traditional cementitious materials

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Abstract

Currently, the need to incorporate recycled materials such as rubber in building products is becoming more important than ever before. The use of waste rubber in mortar/concrete mixtures creates landfill avoidance and decreases the depletion of virgin raw materials. Waste rubber can be used as a part of fine aggregate, coarse aggregate or both aggregates. It can be used as an additive to Portland cement (PC). This paper presents an overview of the previous researches carried out on the use of waste rubber as partially or fully natural fine aggregate replacement in traditional mortar/concrete mixtures based on PC. The effects of rubber sand on workability, setting time, bleeding, density, strength, impact energy, impact load, toughness, ductility, shrinkage, abrasion resistance, freeze/thaw resistance, fire resistance, thermal insulation, carbonation resistance, corrosion resistance, water absorption, porosity, chloride ion penetration, resistance to aggressive environmental, energy absorption, sound absorption, electrical resistance and cracking resistance of rubberised mortar/concrete were reviewed.

Keywords: Waste rubber; Fine aggregate; Fresh properties; Mechanical strength; Durability

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Contents

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1. Introduction

As known, waste generation in the EU was estimated to stand at over 1.43 billion tonnes per year and was increasing at rates comparable to those of economic growth (Martínez et al., 2013). Consequently, waste reduction and recycling are very important elements in a waste management framework because they help to conserve natural resources and reduce the demand for valuable landfill space. Waste rubber is one of the significant wastes which has been a major concern in the world. Data that were collected from the literature has shown that in 2005, over 10 billion tyres are discarded worldwide every year (Alamo-NoleLuis et al., 2011). According to Colom et al. (2007), it was estimated that around 1 billion tyres are withdrawn from use each year. It was estimated that 1000 million tyres reach the end of their useful life every year. By the year 2030, the number can reach up to 1200 million tyres representing almost 5000 million tyres (including stock piled) to be discarded on a regular basis (Pacheco-Torgal et al., 2012). In the United States, for example, there were 2–3 billion tyres deposited in landfills per year (Humphrey, 1995) and 275 million scrap tyres stockpiled across the country, with an increase of 290 million tyres generated per year (Batayneh et al., 2008). It was estimated that one car tyre per person was discarded each year in the developed world and hence 1 billion waste tyres were disposed globally each year (Martínez et al., 2013). It was estimated that approximately 4 billion of waste tyres were in landfills and stockpiles worldwide (Business Council for Sustainable Development, 2011).

The US Environmental Protection Agency reported that 290 million scrap tyres were generated in 2003. Of the 290 million, 45 million of these scrap tyres were used to make automotive and truck tyre re-treads. In Europe every year, 355 million tyres are produced in 90 plants, representing 24% of world production (Presti, 2013). In addition the EU has millions of used tyres that have been illegally dumped or stockpiled. The inadequate disposal of tyres may, in some cases, pose a potential threat to human health (fire risk, haven for rodents or other pests such as mosquitoes) and increase environmental risks. Most countries, in Europe and worldwide, have relied on land filling to dispose of used tyres but the limited space and their potential for reuse has led to many countries imposing a ban on this practice. The current estimate for these historic stockpiles throughout the EU stands at 5.5 million tonnes (1.73 times the 2009 annual used tyres arising) and the estimated annual cost for the management of ELTs is estimated at € 600 million (Presti, 2013).

In UK, approximately 37 million tyres were used annually in 2002. This number continues to grow (Martin, 2001). In Thailand, the record of the year 2000 alone indicated a consumption of approximately 250,000 metric tonnes of rubber products. About 38% of this (94,000 metric tonnes) were vehicle tyres. These numbers keep on increas-

Figure 1. Waste rubber landfill.

ing every year with the numbers of vehicles, as do the future problems relating to waste tyres (Sukontasukkul and Chaikaew, 2006). In Taiwan, over 100,000 tonnes of waste tyres are annually generated, and this number is increasing (Yung et al., 2013). In Australia, the trend for accumulated waste tyres was rising at a rate of 2% and it was estimated more than 20 million tyres were accumulated in landfills by year 2010 (Mohammadi et al., 2014). In France, over 10 million scrap-tyres per year were produced (Siddique and Naik, 2004). The used rubber tyres in Singapore are sent to the incineration plants for disposal and burning. Based on waste statistics and recycling rate for 2008 (Wong and Ting, 2009), from a total scrap tyre waste output of 25,100 tonnes, 3000 tonnes were disposed of, whereas 22,100 tonnes were recycled such that the recycling rate of this waste was approximately 88%. In Spain, 42% of worn tyres generated have been destined to energy recovery, mainly in cement kilns, 10% have been reused and 48% have been destined to material recovery in 2011 (Eiras et al., 2014). In 2010 the EU27 plus Turkey produced about 4.5 million tonnes of tyres, estimated at 17 million tonnes. From this amount, it is assessed that more than 3.2 million tonnes of waste tyres are discarded annually and for this reason the disposal of waste tyres is considered as an increasing environmental and economic problem (Williams et al., 1995).

Most of waste tyres are landfill disposed, which is the most common method (Fig. 1). This method will be drastically reduced in the near future due to the recent introduction of European Union directives that include significant restrictions on this practice in favour of alternatives oriented towards material and energy recovery. In addition, the disposal of used tyres in landfills, stockpiles or illegal dumping grounds increases the risk of accidental fires with uncontrolled emission of potentially harmful compounds (Yung et al., 2013). In order to properly dispose of these millions of waste tyres, the use of innovative techniques to recycle them is important. However, a significant proportion of the waste tyres are used in civil engineering applications such as road and rail foundations and embankments (0.24 million tonnes) re-treaded (0.26 million tonnes) or exported (0.33 million tonnes) each year (ETRMA, 2011). Recycled waste tyres are used for energetic purposes in cement kilns (Siddique and Naik, 2004), incinerated for the production of electricity (Oikonomou and Mavridou, 2009), used as an additive to PC mortar/

concrete (Merino et al., 2007; Al-Akhras and Samadi, 2004; Benazzouk et al., 2004), as a light weight filler (Chen et al., 2013), as crush barriers, bumpers and artificial reefs, etc. (Shu and Huang, 2014).

The worldwide consumption of natural sand as a fine aggregate in mortar/concrete production is very high and several developing countries have encountered some strain in the supply of natural sand in order to meet the increasing needs of infrastructural development in recent years. In many countries there is a scarcity of natural fine aggregate which is suitable for construction. In general, in the last 15 years, it has become clear that the availability of good quality natural sand is decreasing (Rashad, 2013, 2014). The shortage of resources of natural sand opened the door for using by-products as fine aggregate. Reuse of waste rubber as a partial or full replacement of fine aggregate in construction activities not only reduces the demand for extraction of natural raw materials, but also saves landfill space.

Already the literature has useful review papers related to properties of concrete containing scrap-tyre rubber (Siddique and Naik, 2004), mechanical properties of rubber (Pușcă et al., 2010), fresh/hardened properties of rubberised and self-compacting rubberised concrete (Najim and Hall, 2010), pyrolysis of waste tyres (Williams, 2013), recycled tyre rubber modified bitumens for road asphalt mixtures (Presti, 2013) and recycling of waste tyre rubber in asphalt and Portland cement concrete (Shu and Huang, 2014). On the other hand, there is no published literature review paper that reviewed the previous works carried out on the properties of mortar/concrete when fine aggregate was partially or fully replaced with waste rubber. So that, the current review aims to review the previous works carried out on the effect of partial or full replacement of fine aggregate, in traditional mortar/concrete based on PC, with waste rubber on some properties of mortar/concrete. The effects of rubber sand on workability, setting time, bleeding, density, strength, impact energy, impact load, toughness, ductility, shrinkage, abrasion resistance, freeze/thaw resistance, fire resistance, thermal insulation, carbonation resistance, corrosion resistance, water absorption, porosity, chloride ion penetration, resistance to aggressive environmental, energy absorption, sound absorption, electrical resistance and cracking resistance of rubberised mortar/concrete were reviewed.

2. Workability, setting time, segregation and bleeding

2.1. Rubberised mortars

Al-Akhras and Samadi (2004) partially replaced natural sand in mortar mixtures with tyre rubber ash (size 0.15 mm) at levels of 0%, 2.5%, 5%, 7.5% and 10%, by weight. The results showed a reduction in the workability with increasing rubber ash sand content. The reduction in the flow was 7.14%, 12.86%, 19.28% and 25% with the inclusion of 2.5%, 5%, 7.5% and 10% rubber ash sand, respectively. The setting time increased with increasing rubber ash sand content. Marques et al. (2008) partially replaced natural sand in mortar mixtures with rubber (passed in sieve 0.8 mm) at levels of 0% and 12%, by volume. Fixed water/cement (w/c) ratio was used. They reported that the inclusion of rubber sand decreased the workability. Topçu and Demir (2007) studied the workability, by flow, of mortar mixtures containing rubber with particles sizes of either 1–0 mm or 4–1 mm as natural sand replacement at levels of 0%, 10%, 20%, 30% and 40%, by volume. The results showed a reduction in the flow with increasing rubber sand content. The reduction in the flow was 4.84%, 12.9%, 22.04% and 24.19% with the inclusion of rubber sand with particle sizes of 0–1 mm or 1–4 mm. Pierce and Blackwell (2003) partially replaced natural fine aggregate in mortar mixtures with crumb rubber (size 0.6 mm) at levels ranging from 32% to 57%, by volume. They reported that crumb rubber contents as high as 57% can be mixed in flowable fill without noticeable rubber segregation, but there was measurable bleeding. Uygunoğlu and Topçu (2010) partially replaced natural sand (size 4–0 mm) with scrap tyre rubber (size 4–1 mm) in self-consolidating mortar mixtures at levels of 0%, 10%, 20%, 30%, 40% and 50%, by weight. Various water/binder (w/b) ratios were used. They reported that the workability of the mixtures decreased by using scrap rubber particles with low and high volumes. The workability of rubberised mixture dramatically decreased for 50% rubber sand. Pelisser et al. (2012) reported a reduction in the flow table of mortar mixtures containing recycled tyre rubber (maximum size 2.4 mm) as natural sand (maximum size 2.4 mm) replacement at a level of 20%, by volume, whilst the inclusion of 40% and 60% rubber sand increased the flow table. Table 1 summarises the mentioned studies

Table 1
Effect of rubber sand on the workability and bleeding of mortar mixtures.

References	Rubber content (%)	Size (mm)	Effect
Al-Akhras and Samadi (2004)	2.5, 5, 7.5 and 10	0.15	– Reduced workability – Increased setting time
Marques et al. (2008)	12	Passed in sieve 0.8	– Reduced workability
Topçu and Demir (2007)	10, 20, 30 and 40	1–0 and 4–1	– Reduced workability
Pierce and Blackwell (2003)	32–57	0.6	– Increased bleeding
Uygunoğlu and Topçu (2010)	10, 20, 30, 40 and 50	4–0	– Reduced workability
Pelisser et al. (2012)	20, 40 and 60	2.4	– 20% Reduced workability – 40% and 60% increased workability

about the effect of rubber sand on the workability and bleeding of mortar mixtures.

2.2. Rubberised concretes

Wang et al. (2013) reported an increase in the cumulative bleeding with the inclusion of rubber (size 4.75 mm) as natural sand replacement in concrete mixtures at levels of 10%, 20%, 30% and 40%, by volume. The cumulative bleeding increased as the amount of rubber replacement increased.

Mohammadi et al. (2014) accomplished trial concrete mixtures when w/c ratio was 0.35 in which natural sand was partially substituted with crumb rubber at levels of 0%, 20% and 40%, by volume. The workability decreased with increasing rubber sand content. Albano et al. (2005) partially replaced natural sand in concrete mixtures with recycled rubber from automobile tyre at levels of 0%, 5% and 10%, by weight, with particle sizes of 0.29 mm and 0.59 mm. The workability decreased with increasing rubber sand content. The reduction in the slump value was 87.5% and 93.75% with the inclusion of 5% and 10% rubber sand with a particle size of 0.29 mm or 0.59 mm, respectively. They also reported that no segregation was observed in rubberised mixtures. Holmes et al. (2014) reported a reduction in the workability of concrete mixtures by partially replacing natural sand with crumb rubber (size 4.75–0.425 mm) at a level of 7.5%. Guo et al. (2014) partially replaced natural sand in concrete mixtures, containing crushed recycled concrete as coarse aggregate, by crumb rubber (size 1.4–0.85 mm). Natural sand was partially replaced with crumb rubber at levels of 0%, 4%, 8%, 12% and 16%, by volume. Fixed w/c ratio and fixed dosage of naphthalene-based high-range water-reducing were used. Results showed that the inclusion of 4% rubber sand exhibited similar workability to the control mixture. For the remaining replacement levels, the workability decreased with increasing rubber sand content. Youssf et al. (2014) partially replaced natural sand in concrete mixtures with crumb rubber (size 2.36 and 1.18 mm) at levels of 0% 5%, 10% and 20%, by volume. Fixed w/c ratio and fixed dosage of superplasticiser (SP) were used. Results showed that the inclusion of 5% rubber sand exhibited similar workability to the control mixture. For the remaining replacement levels, the workability decreased with increasing rubber sand content. Raj et al. (2011) partially replaced natural sand (maximum size 4.75 mm) with rubber (maximum size 4.75 mm) in SCC mixtures at levels of 0%, 5%, 10%, 15% and 20%, by volume. Various w/b ratios, various dosages of SP and viscosity-modifying admixture were used. They reported a reduction in the workability with increasing rubber sand content. The average reduction in the flow value was approximately 0.47%, 0.94%, 1.96% and 8% with the inclusion of 5%, 10%, 15% and 20% rubber sand, respectively. The flow value decreased with increasing rubber sand content, whilst the V-funnel time and L-box increased with increasing rubber sand content. Ganesan et al. (2013) studied the slump flow of SCC mixtures containing rubber (maximum size 4.75 mm), after suitable treatment with Poly Vinyl Alcohol, as natural sand (maximum size 4.75 mm) replacement at levels of 0%, 15% and 20%, by volume. The results showed a reduction in the slump flow with the inclusion of rubber sand. The reduction in the slump flow was 1.43% and 2.14% with the inclusion of 15% and 20% rubber sand, respectively.

Gesoğlu and Güneyisi (2007) partially replaced natural fine and coarse aggregate in concrete mixtures with crumb rubber (grading close to fine aggregate) and tyre chips, respectively, at levels of 0%, 5%, 15% and 25%, by total aggregate volume. Fixed w/b ratio and fixed dosage of SP were used. The results showed a reduction in the workability with increasing rubber sand content. Ozbay et al. (2011) partially replaced natural crushed limestone sand in concrete mixtures with crumb rubber (size 3–0 mm) at levels of 0%, 5%, 15% and 25%, by volume. Fixed w/c ratio of 0.4 and fixed dosage of SP were used. They reported that the inclusion of rubber sand reduced the workability. The reduction in the slump value was 2.27%, 9.1% and 15.91% with the inclusion of 5%, 15% and 25% rubber sand, respectively. Güneyisi (2010) partially replaced natural sand (maximum size 5 mm) in SCC mixtures with crumb rubber (similar to the natural sand gradation) at levels of 5%, 15% and 25%, by volume. Fixed w/b ratio and various dosages of SP were used. Results showed a reduction in the workability with increasing rubber sand content. They also partially replaced cement with FA at levels of 0%, 20%, 40% and 60%, by weight. They reported that the inclusion of FA amended the fresh properties of the rubberised SCC mixtures. More amended mixture was obtained with increasing the FA content. Initial and final setting times increased with increasing rubber sand content and FA content.

Rahman et al. (2012) partially replaced natural sand in SCC mixtures with rubber (size 4–1 mm) at a level of 28%, by volume. Fixed w/c ratio with two dosages of SP was used. Results showed a reduction in the workability with the inclusion of rubber sand. Topçu and Demir (2007) studied the workability of concrete mixtures containing rubber (size 4–1 mm) as a natural sand replacement at levels of 0%, 10%, 20% and 30%, by volume. Results showed a reduction in the workability with increasing rubber sand content. The reduction in the slump value was 3.1%, 6.2% and 8.53% with the inclusion of 10%, 20% and 30% rubber sand, respectively. Karahan et al. (2012) partially replaced natural sand in SCC mixtures with crumb rubber (size 4.75–0.15 mm) at levels of 0%, 10%, 20% and 30%, by volume. Fixed w/b ratio of 0.32 and various dosages of high range water reducer (HRWR) were used. Results showed a reduction in the filling and passing ability of SCC mixtures with the inclusion of rubber sand. Grdić et al. (2014) reported a reduction in the workability of concrete mixtures by partially replacing natural sand with rubber (size 4–0.5 mm) at levels of 10%, 20% and 30%, by volume. Güneyisi et al. (2004) studied the workability of concrete mixtures containing crumb rubber (maximum particle size 4 mm) as natural fine aggregate replacement and tyre chips (size 40–10 mm) as natural coarse aggregate replacement at levels ranging from 2.5% to 50%, by total aggregate volume. Various w/c ratios were used. They reported a reduction in the workability with the inclusion of rubber aggregate. This reduction increased as the content of rubber aggregate increased.

Batayneh et al. (2008) studied the workability of concrete mixtures containing crumb rubber. Natural sand (size 4.75–0.15 mm) was replaced with crumb rubber (size 4.75–0.15 mm) at levels of 0%, 20%, 40%, 60%, 80% and 100%, by volume. Results showed a reduction in the workability with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the slump value was 19.42%, 52.61%, 76.5%, 86.33% and 93.76% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber sand, respectively. Taha et al. (2008) replaced natural sand in concrete mixtures with crumb rubber (size 5–1 mm) at levels of 0%, 25%, 50%, 75% and 100%, by volume. Fixed w/c ratio was used. Results showed a reduction in the workability with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the slump value was approximately 13.33%, 40%, 66.67% and 80% with the inclusion of 25%, 50%, 75% and 100% rubber sand, respectively. Khatib and Bayomy (1999) studied the workability of concrete mixtures containing crumb rubber (gradation close to the natural sand) as natural sand replacement. Natural sand was replaced with crumb rubber at levels ranging from 5% to 100%, by volume. Results showed that the workability decreased with increasing rubber sand content.

On the other hand, Pelisser et al. (2012) partially replaced natural sand in concrete mixtures with recycled tyre rubber (size < 4.8 mm) at levels of 0%, 10%. Fixed w/c ratio and various dosages of plasticiser were used. They reported an increase in the workability with the inclusion of rubber sand. The increase in the slump value was 63.63% with the inclusion of rubber sand. Bravo and de Brito (2012) partially replaced natural sand in concrete mixtures with rubber aggregate made from used tyres (with the same size of the natural sand) at levels of 0%, 5%, 10% and 15%, by volume. Various w/c ratios were used. Results showed a reduction in the workability with the inclusion of 5% and 15% rubber sand, whilst the inclusion of 10% rubber sand increased it. Onuaguluchi and Panesar (2014) partially replaced natural fine aggregate in concrete mixtures with crumb rubber (size ~86% of rubber particles smaller than 2.3 mm) at levels of 0%, 5%, 10% and 15%, by volume. Fixed w/c ratio and fixed dosage of HRWR were used. Results showed an increase in the workability with the inclusion of rubber sand. The workability increased with increasing rubber sand content. Antil et al. (2014) reported an increase in concrete mixture workability by partially replacing natural sand with 5% and 10% crumb rubber (size 4.75–0.075 mm), by volume, whilst the inclusion of 15% and 20% rubber sand reduced it. Parveen et al. (2013) partially replaced natural sand in concrete mixtures with crumb rubber (size 4.75–0.075 mm) at levels of 0%, 5%, 10%, 15% and 20%, by volume. Results showed an increase in the workability with the inclusion of 5% and 10% rubber sand, whilst the inclusion of 15% and 20% rubber sand decreased it. Balaha et al. (2007) reported higher workability of concrete mixtures containing ground waste tyre rubber (size < 4 mm) as partial replacement of natural sand at levels of 0%, 5%, 10%, 15% and 20%, by volume. Results showed an increase in the workability as rubber sand content increased. Azmi et al. (2008) reported an increase in the workability of concrete mixtures by replacing natural sand with crumb rubber (size 2.36–2 mm) at levels of 0%, 10%, 15%, 20% and 30%, by volume. The workability increased with increasing rubber sand content.

Wang et al. (2013) studied the workability and initial setting time of low strength rubber concrete (CLSRC) mixtures and low strength lightweight concrete (CLSRLC) mixtures at different contents of rubber. Natural sand was partially replaced with rubber (size 4.75 mm) at levels of 0%, 10%, 20%, 30% and 40%, by volume. Fixed w/b ratio and fixed dosage of accelerating agent were used. For CLSRC mixtures, the results showed 3.46% increase in the slump value with the inclusion of 10% rubber sand, whilst the reduction in the slump value reached 4.33%, 1.3% and 14.72% with the inclusion of 20%, 30% and 40% rubber sand, respectively. The slump flow increased with the inclusion of 10% and 20% rubber sand, whilst the inclusion of 30% and 40% rubber sand decreased it. The initial setting time increased with increasing rubber sand content. The increase in the initial setting time was 8%, 15.47%, 28.27% and 42.4% with the inclusion of 10%, 20%, 30% and 40% rubber sand, respectively. For CLSRLC mixtures, the results showed an 8% increase in the slump value with the inclusion of either 10% or 20% rubber sand, whilst the reduction in the slump value reached 12% and 14% with the inclusion of 30% and 40% rubber sand, respectively. The initial setting time results showed similar trend as CLSRC mixtures. Topçu and Sarıdemir (2008) partially replaced natural fine aggregate in concrete mixtures by rubber with two particle sizes of 1–0 mm and 4–1 mm at levels of 0%, 15%, 30% and 45%, by volume. They reported that with the increase of rubber content in concrete mixtures as fine aggregate replacement, the flow table value increased. The greatest flow table value was observed in the coarse rubberised concrete mixture as 8.33%, whilst the smallest was observed in the fine rubberised concrete mixture as 1.08%. Turgut and Yesilata (2008) partially replaced natural sand in concrete block mixtures with rubber (size 4.75–0.075 mm) at levels ranging from 10% to 70% with an increment of 10%, by volume. Results showed an increase in the workability with the inclusion of rubber sand up to 40%, whilst the inclusion of 50–70% rubber sand decreased it. Khaloo et al. (2008) studied the workability of concrete mixtures containing crumb rubber. Natural sand (maximum size 4.75 mm)

Table 2
Effect of rubber sand on the workability, setting time, segregation and bleeding of concrete mixtures.

References	Rubber content (%)	Size (mm)	Effect
Wang et al. (2013)	10, 20, 30 and 40	4.75	– Increased bleeding
Mohammadi et al. (2014)	20 and 40	–	– Reduced workability
Albano et al. (2005)	5 and 10	0.29 and 0.59	– Reduced workability – No segregation
Holmes et al. (2014)	7.5	4.75–0.425	– Reduced workability
Guo et al. (2014)	4, 8, 12 and 16	1.4–0.85	– Reduced workability
Youssf et al. (2014)	5, 10 and 20	2.36 and 1.18	– Reduced workability
Raj et al. (2011)	5, 10, 15 and 20	4.75	– Reduced workability
Ganesan et al. (2013)	15 and 20	4.75	– Reduced workability
Gesoğlu and Güneyisi (2007)	5, 15 and 25	Close to fine aggregate	– Reduced workability
Ozbay et al. (2011)	5, 15 and 25	3–0	– Reduced workability
Güneyisi (2010)	5, 15 and 25	Similar to sand gradation	– Reduced workability – Increased initial and final setting time – FA amended fresh properties and increased setting time
Rahman et al. (2012)	28	4–1	– Reduced workability
Topçu and Demir (2007)	10, 20 and 30	4–1	– Reduced workability
Karahan et al. (2012)	10, 20 and 30	4.75–0.15	– Reduced workability
Grdić et al. (2014)	10, 20 and 30	4–0.5	– Reduced workability
Batayneh et al. (2008)	20, 40, 60, 80 and 100	4.75–0.15	– Reduced workability
Taha et al. (2008)	25–100	5–1	– Reduced workability
Khatib and Bayomy (1999)	5–100	Close to sand	– Reduced workability
Pelisser et al. (2011)	10	<4.8	– Increased workability
Bravo and de Brito (2012)	5, 10 and 15	Similar to sand gradation	– 5% and 15% reduced workability – 10% increased workability
Onuaguluchi and Panesar (2014)	5, 10 and 15	~86% smaller than 2.3 mm	– Increased workability
Antil et al. (2014)	5, 10, 15 and 20	4.75–0.075	– 5% and 10% increased workability – 15% and 20% reduced workability
Parveen et al. (2013)	5, 10, 15 and 20	4.75–0.075	– 5% and 10% increased workability – 15% and 20% reduced workability
Balaha et al. (2007)	5, 10, 15 and 20	<4	– Increased workability
Azmi et al. (2008)	10, 15, 20 and 30	2.36–2	– Increased workability
Wang et al. (2013)	10, 20, 30 and 40	4.75	For CLSRC – Increased initial setting time – 10% increased workability – 20%, 30% and 40% reduced workability
Wang et al. (2013)	10, 20, 30 and 40	4.75	For CLSRLC – Increased initial setting time – 10% and 20% increased workability – 30% and 40% reduced workability
Topçu and Sarıdemir (2008)	15, 30 and 45	1–0 and 4–1	– Increased workability
Turgut and Yesilata (2008)	10–70	4.75–0.075	– Up to 40% increased workability –50–70% reduced workability
Khaloo et al. (2008)	25, 50, 75 and 100	4.75	– 25%, 50% and 75% increased workability – 100% reduced workability

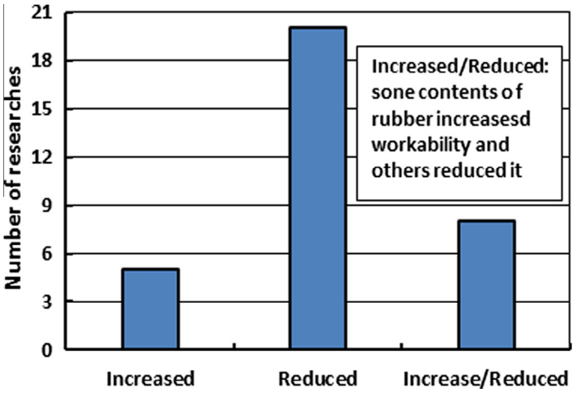

Figure 2. Research numbers versus the effect of waste rubber sand on the workability of mixtures.

was replaced with crumb rubber (maximum size 4.75 mm) at levels of 0%, 25%, 50%, 75% and 100%, by volume. Results showed an increase in the workability with the inclusion of 25%, 50% and 75% rubber sand. The inclusion of 25% rubber sand showed the highest workability followed by 75% and 50%, respectively. On the other hand, the inclusion of 100% rubber sand significantly decreased it. Table 2 summarises the mentioned studies about the effect of rubber sand on the workability, setting time, segregation and bleeding of concrete mixtures.

From the above review of the literature in Sections 2.1 and 2.2, it can be noted that several studies reported that the inclusion of waste rubber sand in the mixture reduced the workability (Fig. 2). This may be related to the higher water absorption of rubber sand compared to natural sand.

The reduction in the workability is mainly depending on rubber content and its particle size. On the contrary, few studies believed that the inclusion of rubber to the mixture increased the workability (Fig. 2). It is worth mentioning that a few other studies believed that some rubber sand contents reduced workability, whilst other contents increased it (Pelisser et al., 2012; Balaha et al., 2007; Khaloo et al., 2008). The reduction in the workability of the mixture with the inclusion of rubber sand is one advantage of the disadvantages of using this recycled material.

3. Density

3.1. Fresh density

Skripkiūnas et al. (2007) partially replaced natural sand in concrete mixtures with rubber (size 1–0 mm) at levels of 0% and 3.2%, by weight. Fixed w/c ratio and fixed dosage of SP were used. The concrete mixture density reduced by 0.66% with the inclusion of rubber sand. Albano et al. (2005) reported a reduction in the fresh density of concrete mixtures containing rubber from automobile at levels of 5% and 10%, by weight. The reduction in the fresh density was 20.33% and 29.58% with the inclusion of 5% and 10% rubber sand with a particle size of 0.59 mm, whilst it was 22.51% and 38.2%, respectively with the inclusion of rubber sand with a particle size of 0.29 mm. Pedro et al. (2013) reported a reduction in the fresh density of mortar mixtures by partially replacing natural sand with shredded rubber (size 2–0 mm) at different levels, by volume. This reduction increased with increasing rubber sand content. The reduction in the fresh density was 4.17%, 7.21% and 10% with the inclusion of 5%, 10% and 15% rubber sand, respectively. Bravo and de Brito (2012) reported a reduction in the fresh density of concrete mixtures containing rubber made from used tyres (with the same size of the natural sand) as natural sand replacement at levels of 0%, 5%, 10% and 15%, by volume. This reduction in the fresh density increased with increasing rubber sand content. Gesoğlu et al. (2014) reported approximately 1.41% and 6.85% reduction in the fresh density of concrete mixtures by partially replacing natural aggregate with rubber (size 4 mm) at levels of 10% and 20%, by total aggregate volume, respectively. Thomas et al. (2014) reported a reduction in the fresh density of concrete mixtures by partially replacing natural sand with discarded tyre rubber (40% powder from mesh 30, 35% size 2–0.8 mm and 25% size 4–2 mm) up to 20%. This reduction increased with increasing rubber sand content. The reduction ranging from 1% with the inclusion of 2.5% rubber sand to 13.23% with the inclusion of 20% rubber sand, at w/c ratio of 0.4. Balaha et al. (2007) reported a reduction in the fresh unit weight of concrete mixtures by partially replacing natural sand with ground waste tyre rubber (size < 4 mm) at levels of 5%, 10%, 15% and 20%, by volume. This reduction increased as the rubber sand content increased. Gesoğlu and Güneyisi (2007) reported a reduction in the fresh unit weight of concrete mixtures containing crumb rubber (grading close to the natural fine aggregate) and tyre chips as fine and coarse aggregate replacement, respectively, at levels of 0%, 5%, 15% and 25%, by total aggregate volume. The fresh unit weight decreased as the rubber content increased. Ozbay et al. (2011) reported a reduction in the fresh unit weight of concrete mixtures with the inclusion of crumb rubber (size 3–0 mm) as natural fine aggregate replacement. The reduction in the fresh unit weight was 0.91%, 3.32% and 5% with the inclusion of 5%, 15% and 25% rubber sand, respectively. Grdić et al. (2014) reported a reduction in the fresh density of concrete mixtures by partially replacing natural sand with rubber (size 4–0.5 mm) at levels of 10%, 20% and 30%, by volume. The reduction in the fresh density increased with increasing rubber sand content. The reduction in the fresh density was 3.8%, 9.3% and 13.3% with the inclusion of 10%, 20% and 30% rubber sand, respectively.

Fadiel et al. (2014) partially replaced natural sand in mortar mixtures with crumb rubber with different sizes at levels of 10%, 20%, 30% and 40%, by weight. Fixed w/c ratio was used. Results showed a reduction in the fresh unit weight of mortar mixtures with the inclusion of rubber sand. The reduction in the fresh unit weight was 10%, 20.94%, 27.1% and 35.37% with the inclusion of 10%, 20%, 30% and 40% rubber sand (size 0.6–0 mm), respectively, whilst the inclusion of rubber sand with a size of 2–0.84 mm reduced it by 6.1%, 15.88%, 21.59% and 29.46%, respectively. Mohammadi et al. (2014) reported a reduction in the fresh density of concrete mixtures by partially replacing natural sand with crumb rubber (after treatment in water-soaking) at levels of 10%, 20%, 30% and 40%, by volume. This reduction increased with increasing rubber sand content. At w/c ratio of 0.45, the reduction in the fresh density was approximately 2.47%, 4.81%, 7.42% and 11.81% with the inclusion of 10%, 20%, 30% and 40% rubber sand, respectively. Topçu and Sarıdemir (2008) reported that rubber (size 1–0 mm or 4–1 mm) at levels of 15%, 30% and 45% as natural fine aggregate replacement, by volume, decreased the fresh unit weight

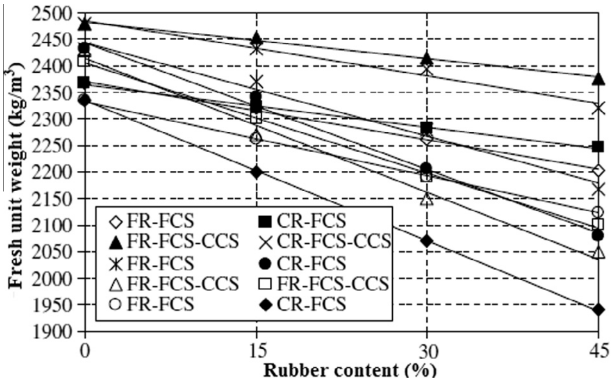

Figure 3. Effect rubber content on the fresh unit weight of concrete mixtures (Topçu and Sarıdemir, 2008).

Table 3
Effect of rubber sand on the reduction percentage of the fresh unit weight of concrete mixtures.

References	Rubber content (%)	Size (mm)	% Reduction
Skripkiūnas et al. (2007)	3.2	1–0	0.66
Albano et al. (2005)	5 and 10	0.59	20.33 and 29.58
Albano et al. (2005)	5 and 10	0.29	22.51 and 38.2
Pedro et al. (2013)	5, 10 and 15	2–0	4.17, 7.21 and 10
Gesoğlu et al. (2014)	10 and 20	4	1.41 and 6.85
Thomas et al. (2014)	2.5–20	Mesh 30, 2–0.8 mm, 4–2 mm	From 1 to 13.22
Ozbay et al. (2011)	5, 15 and 25	3–0	0.91, 3.32 and 5
Grdić et al. (2014)	10, 20 and 30	4–0.5	3.8, 9.3 and 13.3
Fadiel et al. (2014)	10, 20, 30 and 40	0.6–0	10, 20.94, 27.1 and 35.37
Fadiel et al. (2014)	10, 20, 30 and 40	2–0.84	6.1, 15.88, 21.59 and 29.46
Mohammadi et al. (2014)	10, 20, 30 and 40	–	2.47, 4.81, 7.42 and 11.81
Topçu and Sarıdemir (2008)	45	1–0	1.13
Topçu and Sarıdemir (2008)	45	4–1	16.92
Taha et al. (2008)	25, 50, 75 and 100	5–1	11.57, 14.35, 17.13 and 21.48
Khaloo et al. (2008)	25, 50, 75 and 100	Maximum 4.75	15.46, 28.66, 34 and 34.79
Batayneh et al. (2008)	20, 40, 60, 80 and 100	4.75–0.15	7.59, 13.78, 17.17, 23.69 and 27.44

of concrete mixtures (Fig. 3). The reduction in the fresh unit weight values of coarse rubberised concrete mixtures was greater than that of fine rubberised concrete mixtures. The greater reduction in the fresh unit weight values was observed in coarse rubberised concrete mixture as 16.92%, whilst the smallest was observed in fine rubberised concrete mixture as 1.13%. Güneyisi et al. (2004) reported a reduction in the fresh unit weight of concrete mixtures containing rubber (maximum particle size 4 mm) as natural fine aggregate replacement and tyre chips (size 40–10 mm) as natural coarse aggregate replacement at levels ranging from 2.5% to 50%, by total aggregate volume. This reduction increased as the rubber aggregate content increased. Taha et al. (2008) reported a reduction in the fresh unit weight of concrete mixtures by replacing natural sand, up to 100%, with rubber (size 5–1 mm). The fresh density decreased with increasing rubber sand content. The reduction in the fresh density was approximately 11.57%, 14.35%, 17.13% and 21.48% with the inclusion of 25%, 50%, 75% and 100% rubber sand, respectively. Khaloo et al. (2008) found a reduction in the fresh unit weight of concrete mixtures by replacing natural sand (maximum size 4.75 mm) with crumb rubber (maximum size 4.75 mm) at levels of 25%, 50%, 75% and 100%, by volume. This reduction increased as the rubber sand content increased. The reduction in the fresh unit weight was approximately15.46%, 28.66%, 34% and 34.79% with the inclusion of 25%, 50%, 75% and 100% rubber sand, respectively. Batayneh et al. (2008) found a reduction in the fresh unit weight of concrete mixtures by replacing natural sand (size 4.75–0.15 mm) with crumb rubber (size 4.75–0.15 mm), by volume. This reduction increased as the rubber sand content increased. The reduction in the fresh unit weight was 7.59%, 13.78%, 17.17%, 23.69% and 27.44% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber sand, respectively. Table 3 summarises the mentioned studies about the effect of rubber sand on the reduction percentage of the fresh unit weight of concrete mixtures.

3.2. Hardened density

Pierce and Blackwell (2003) reported a reduction in the mortar mass density by partially replacing natural fine aggregate with crumb rubber (size 0.6 mm) at levels ranging from 32% to 57%, by volume. This reduction increased as the rubber sand content increased. Mohammed et al. (2012) reported that hollow concrete blocks containing rubber (size 0.6 mm) as natural sand replacement produced lightweight blocks compared to the normal weight hollow blocks. Skripkiūnas et al. (2007) partially replaced natural sand in concretes with rubber (size 1–0 mm) at levels of 0% and 3.2%, by weight. The hardened density of concrete reduced by 0.85% with the inclusion of rubber sand. Pelisser et al. (2011) found a 13% reduction in the concrete density by partially replacing natural sand with 10% recycled tyre rubber (size < 4.8 mm). Sukontasukkul and Chaikaew (2006) partially replaced natural fine and coarse aggregate with crumb rubber in concrete blocks at levels of 0%, 10% and 20%, by weight. Results showed a reduction in the dry density of the specimens with increasing rubber sand content. Raj et al. (2011) reported a reduction in the hardened density of SCCs by partially replacing natural sand with rubber (maximum size 4.75 mm) at levels of 0%, 5%, 10%, 15% and 20%, by volume. This reduction increased with increasing rubber sand content.

Pedro et al. (2013) reported a reduction in the dry bulk density of mortar specimens by partially replacing natural sand with shredded rubber (size 2–0 mm) at different levels, by volume. This reduction increased with increasing rubber sand content. The reduction in the 28 days dry bulk density was 4.32%, 7.45% and 9.9% with the inclusion of 5%, 10% and 15% rubber sand, respectively, whilst, it reached 4.83%, 7.8% and 11.11% at the age of 90 days, respectively. Onuaguluchi and Panesar (2014) reported a reduction in the dry unit weight of concretes with the inclusion of crumb rubber (size ~86% smaller than 2.3 mm) as natural fine aggregate replacement, by volume. The reduction in the dry unit weight was 1.75%, 2.58% and 7% with the

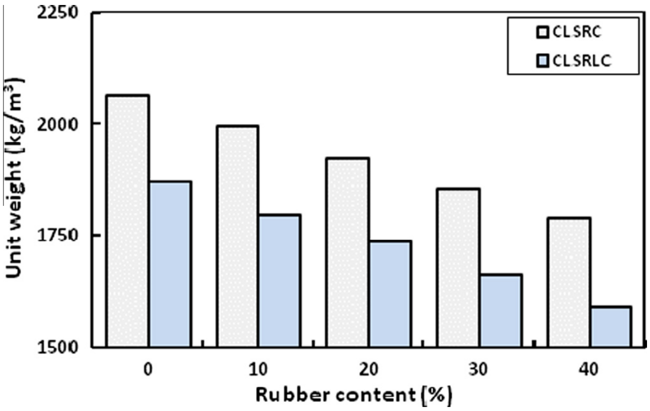

Figure 4. Effect of rubber sand content on the dry unit weight of CLSRC and CLSRLC (Wang et al., 2013).

inclusion of 5%, 10% and 15% rubber sand, respectively. Corinaldesi et al. (2011) employed styrene butadiene rubber (SBR) or waste rubber-shoe (SR) as a part of fine aggregate in mortars. Natural sand (size 5–0 mm) was partially replaced with either SBR (size 12–0 mm) or SR (size 8–0 mm) at levels of 0%, 10% and 30%, by volume. The dry unit weight of the mortars decreased with increasing rubber sand content. The reduction in the dry unit weight was 3.84% and 16.35% with the inclusion of 10% and 30% SBR sand, respectively, whilst it was 2.86% and 13.54% with the inclusion of 10% and 30% SR sand, respectively. Sukontasukkul (2009) partially replaced natural sand in concretes with two different particle sizes of rubber at levels of 0%, 10%, 20% and 30%, by volume. The sizes of crumb rubber were No. 6 (passing sieve No. 6) and No. 26 (passing sieve No. 26). Results showed a reduction in the hardened density of concrete specimens with increasing rubber sand content. The reduction in the hardened density was approximately 14.23%, 16.6% and 19.76% with the inclusion of 10%, 20% and 30% rubber sand with large size, respectively, whilst it was approximately 17.39%, 22.13% and 28.06%, respectively, with the inclusion of rubber sand with small size. In another investigation, Sukontasukkul and Tiamlom (2012) partially replaced natural sand in concretes with two different particle sizes of rubber at levels of 0%, 10%, 20% and 30%, by volume. The sizes of crumb rubber were No. 6 (passing sieve No. 6) and No. 26 (passing sieve No. 26). Results showed a reduction in the hardened density of concrete specimens with increasing rubber sand content. The reduction in the hardened density was approximately 3.66%, 9.76% and 12.19% with the inclusion of 10%, 20% and 30% rubber sand with large size, respectively, whilst it was approximately 9.76%, 13.42% and 16.46%, respectively, with the inclusion of rubber sand with small size. Grdić et al. (2014) reported a reduction in the hardened density of concrete specimens by partially replacing natural sand with rubber (size 4–0.5 mm) at levels of 10%, 20% and 30%, by volume. The reduction in the hardened density increased with increasing rubber sand content. The reduction in the hardened density was 4.64%, 9.49% and 13.2% with the inclusion of 10%, 20% and 30% rubber sand, respectively. Hilal (2011) reported a reduction in the hardened density of foamed concrete specimens by partially replacing natural sand with crumb rubber (size 5–0.7 mm) at levels of 20% and 30%, by weight. The reduction in the 28 days density was 6.4% and 10.4% with the inclusion of 20% and 30% rubber sand, respectively. Fadiel et al. (2014) partially replaced natural sand in mortars with crumb rubber (size 0.6–0 or 2–0.84) at levels of 10%, 20%, 30% and 40%, by weight. Fixed w/c ratio was used. Results showed a reduction in the dry density of mortar specimens with the inclusion of rubber sand. The reduction in the density reached 8%, 20.66%, 28% and 39% with the inclusion of 10%, 20%, 30% and 40% rubber sand (size 0.6–0 mm), respectively, whilst the inclusion of rubber sand with size of 2–0.84 mm reduced it by 3.25%, 13.94%, 21.21% and 30.1%, respectively. Gisbert et al. (2014) partially replaced natural sand in mortars with two different fineness of crumb rubber at levels of 0%, 10%, 20%, 30% and 40%, by weight. 80% of residue was retained in the size of 0.25 mm for fine rubber particles, whilst 80% of residue was retained in the size of 2.0 mm for coarse rubber particles. Results showed a reduction in the density with the inclusion of rubber sand. The reduction in the density was 9.62%, 12.14%, 14% and 17.14% with the inclusion of 10%, 20%, 30% and 40% fine rubber sand, respectively, whilst it was 17.35%, 11.74%, 21.48% and 28.64% with the inclusion of coarse rubber sand, respectively.

Wang et al. (2013) reported a reduction the unit weight of concrete specimens by partially replacing natural sand with rubber (size 4.75 mm) at levels ranging from 0% to 40%, by volume. This reduction increased as the content of rubber sand increased (Fig. 4). Turki et al. (2009) partially replaced natural sand (size 2–0 mm) in concretes with rubber made from shredded worn tyres (size 4–1 mm) upto 50%, by volume. They reported a reduction in the dry bulk density of concretes with increasing rubber sand content. The reduction in the dry bulk density was 2.76%, 6.4%, 13.43%, 16.78% and 22.3% with the inclusion of 10%, 20%, 30%, 40% and 50% rubber sand, respectively. Uygunoğlu and Topçu (2010) reported a reduction in the dry unit weight of mortars containing scrap tyre rubber (size 4–1 mm) as natural sand replacement (size 4–0 mm) at levels ranging from 10% to 50%, by weight. This reduction increased with increasing rubber sand content. At w/b ratio of 0.4, the reduction in the dry unit weight was approximately 3.9%, 4.44%, 8.81%, 11.35% and 16% with the inclusion of 10%, 20%, 30%, 40% and 50% rubber sand, respectively. Ling, 2011 studied the hardened density of concrete blocks manufactured with different w/c ratios of 0.45, 0.5 and 0.55 containing rubber (size 5–1 mm) as natural sand (size 4 mm) replacement at levels ranging from 5% to 50%, by volume. Results showed a reduction in the hardened density with increasing rubber sand content at all w/c ratios. At w/c ratio of 0.45, the reduction in the hardened density was 0.88%, 1.95%, 2.59%, 3.71%, 4.59%, 6.54%, 7.28% and 7.65% with the inclusion of 5%, 10%, 15%, 20%, 25%, 30%, 40% and 50% rubber sand, respectively, whilst it was 1.27%, 2.08%, 1.72%, 3.21%, 3.57%, 5.34%, 5.83% and 8.41%, respectively, at w/c ratio of 0.55. Turki et al. (2009) partially replaced natural sand (size 2–0 mm) in mortars with rubber (size 4–1 mm, maximum grain size was 3.15 mm) at levels of 0%, 10%, 30% and 50%, by volume. Fixed w/c ratio of 0.5 was used. Results showed a reduction in the dry bulk density of mortar specimens with increasing rubber sand content. The reduction in the dry bulk density was 3.64%, 16.3% and 20.85% with the inclusion of 10%, 30% and 50% rubber sand, respectively.

Eiras et al. (2014) reported a reduction in the dry bulk density of mortars by partially replacing natural sand with crumb rubber (size ~0.08–1.3 mm) at levels of 40%, 50% and 60%, by volume. The reduction in the dry bulk density was approximately 18.69%, 25.23% and 27.1% with the inclusion of 40%, 50% and 60% rubber sand, respectively. Turgut and Yesilata (2008) reported a reduction in the unit weight of concrete blocks by partially replacing natural sand with crumb rubber (4.75–0.075 mm) at different levels, by volume. The reduction of the unit weight increased with increasing rubber sand content. The reduction in the unit weight was 2.76%, 6.45%, 10.14%, 15.21%, 20.28%, 26.27% and 29.49% with the inclusion of 10%, 20%, 30%, 40%, 50%, 60% and 70% rubber sand, respectively. El-Gammal et al. (2010) replaced natural sand in concretes with crumb rubber (size ~5–0.2 mm) at levels of 0%, 50% and 100%, by weight. Results showed a reduction in the density of concrete specimens with the inclusion of rubber sand. The reduction reached 9.42% and 13.45% with the inclusion of 50% and 100% rubber sand, respectively. Atahan and Yüce (2012) replaced natural fine aggregate and coarse aggregate in concretes with crumb rubber at levels of 0%, 20%, 40%, 60%, 80% and 100%, by volume. The small rubber particles that were used to replace natural sand passed mesh sizes of 10 and 20, whilst large rubber particles that passed through a 13 mm screen were used to replace natural coarse aggregate. The unit weight of the concrete specimens decreased with increasing rubber aggregate content. The reduction in the unit weight was approximately 10.39%, 16.24%, 20.78%, 35.26% and 42.86% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber sand, respectively. Taha et al. (2008) reported a reduction in the hardened density of concretes by replacing natural sand, up to 100%, with rubber (size 5–1 mm). The hardened density decreased with increasing rubber sand content. The reduction in the hardened density was 9.35%, 13.36%, 16.44% and 19.16% with the inclusion of 25%, 50%, 75% and 100% rubber sand, respectively. On

Table 4
Effect of rubber content on the dry unit weight of mortars and concretes.

References	Rubber content (%)	Size (mm)	Type	% Reduction
Skripkiūnas et al. (2007)	3.2	1–0	Concrete	0.85
Pelisser et al. (2011)	10	<4.8	Concrete	13
Pedro et al. (2013)	5, 10 and 15	2–0	Mortar	4.32, 7.45 and 9.9
Onuaguluchi and Panesar (2014)	5, 10 and 15	~86% smaller than 2.3 mm	Concrete	1.75, 2.58 and 7
Corinaldesi et al. (2011)	10 and 30 (SBR)	12–0	Mortar	3.84 and 16.35
Corinaldesi et al. (2011)	10 and 30 (SR)	8–0	Mortar	2.86 and 13.54
Sukontasukkul (2009)	10, 20 and 30	Passing sieve No. 6	Concrete	14.23, 16.6 and 19.76
Sukontasukkul (2009)	10, 20 and 30	Passing sieve No. 26	Concrete	17.39, 22.13 and 28.06
Sukontasukkul and Tiamlom (2012)	10, 20 and 30	Passing sieve No. 6	Concrete	3.66, 9.76 and 12.19
Sukontasukkul and Tiamlom (2012)	10, 20 and 30	Passing sieve No. 26	Concrete	9.76, 13.42 and 16.46
Grdić et al. (2014)	10, 20 and 30	4–0.5	Concrete	4.64, 9.49 and 13.2
Hilal (2011)	20 and 30	5–0.7	Concrete	6.4 and 10.4
Fadiel et al. (2014)	10, 20, 30 and 40	0.6–0	Mortar	8, 20.66, 28 and 39
Fadiel et al. (2014)	10, 20, 30 and 40	2–0.84	Mortar	3.25, 13.94, 21.21 and 30.1
Gisbert et al. (2014)	10, 20, 30 and 40	80% returned 0.25	Mortar	9.62, 12.14, 14 and 17.14
Gisbert et al. (2014)	10, 20, 30 and 40	80% returned 2	Mortar	17.35, 11.74, 21.48 and 28.64
Turki et al. (2009)	10, 20, 30, 40 and 50	4–1	Concrete	2.76, 6.4, 13.43, 16.78 and 22.3
Uygunoğlu and Topçu (2010)	10, 20, 30, 40 and 50	4–1	Mortar	3.9, 4.44, 8.81, 11.35 and 16 (w/c = 0.4)
Ling (2011)	5, 10, 15, 20, 25, 30, 40 and 50	5–1	Concrete	0.88, 1.95, 2.59, 3.71, 4.59, 6.54, 7.28 and 7.65 (w/c = 0.45)
Ling (2011)	5, 10, 15, 20, 25, 30, 40 and 50	5–1	Concrete	1.27, 2.08, 1.72, 3.21, 3.57, 5.34, 5.83 and 8.41 (w/c = 0.55)
Turki et al. (2009)	10, 30 and 50	4–1	Mortar	3.64, 16.3 and 20.85
Eiras et al. (2014)	40, 50 and 60	~0.08–1.3	Mortar	18.69, 25.23 and 27.1
Turgut and Yesilata (2008)	10–70	4.75–0.075	Concrete block	2.76–29.49
El-Gammal et al. (2010)	50 and 100	~5–0.2	Concrete	9.42 and 13.45
Taha et al. (2008)	25, 50, 75 and 100	5–1	Concrete	9.35%, 13.36%, 16.44% and 19.16%

the other hand, Ling (2012) reported an increase in the hardened density of concrete with the inclusion of 10% rubber as natural sand replacement, by volume, whilst the inclusion of 20% and 30% rubber sand decreased it. The hardened density increased by 3.63% with the inclusion of 10% rubber sand, whilst the inclusion of 20% and 30% rubber sand decreased it by 3.34% and 7%, respectively. Table 4 summarises the mentioned studies about the effect of rubber sand on the dry unit weight of mortars and concretes.

From the above review of the literature in Sections 3.1 and 3.2, it can be noted that the inclusion of rubber sand in the mixture decreased the fresh and hardened density. This reduction in the density is related to the physical properties of rubber, since it has lower density than natural sand, hence it occupies greater volume (Albano et al., 2005). This effect is more pronounced for smaller rubber particles, due to the greater porosity of the composite obtained; this means greater quantity of spaces filled with water within the interface rubber-concrete (Albano et al., 2005). Gesoğlu and Güneyisi (2007), Turki et al. (2009) and Thomas et al. (2014) related the reduction in the unit weight of the rubberised mixture to the lower specific gravity of rubber. Raj et al. (2011) related the reduction in the hardened density of rubberised concrete to the relatively lower density of rubber compared to natural sand. Taha et al. (2008) attributed the reduction in the fresh and hardened unit weight of rubberised concrete to two factors: first, the ability of rubber particles to entrap air in its jagged surface texture; and second, to the low specific gravity of the rubber particles compared to conventional aggregate. The reduction in the density with the inclusion of rubber sand is one advantage of using this recycled material. This also could be a courage factor to use rubber sand in concrete in some engineering applications such as lightweight concrete.

4. Mechanical strength

4.1. Rubberised mortars

4.1.1. Replacement levels up to 15%

Al-Akhras and Samadi (2004) reported an increase in the compressive and flexural strength at ages of 3, 7, 28 and 90 days by partially replacing natural sand in mortars with rubber ash (size 0.15 mm) at levels of 2.5%, 5%, 7.5% and 10%, by weight. The strength increased with increasing rubber ash content. The enhancement in the 28 days compressive strength was 12%, 14%, 23% and 40% with the inclusion of 2.5%, 5%, 7.5% and 10% rubber ash sand, respectively, whilst the enhancement in the 28 days flexural strength was 12%, 27%, 32% and 43%, respectively. On the other hand, Segre et al. (2004) studied flexural strength of mortars containing 10% rubber (size 0.2 mm) as natural sand replacement, by weight. Results showed 25% reduction in the flexural strength with the inclusion of rubber sand. Marques et al. (2008) reported a reduction in the compressive strength, splitting tensile strength and modulus of elasticity of mortars, at ages of 7, 28, 56 and 90 days, by partially replacing 12% natural sand with rubber (passed in sieve 0.8 mm), by volume. Oikonomou and Mavridou (2009) partially replaced natural sand in mortars with worn automobile tyre rubber (size 1.18–0.75 mm) at levels of 0%, 2.5%, 5%, 7.5%, 10%, 12.5% and 15%, by weight. Fixed w/c ratio was used. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber sand. The reduction in the compressive strength was 24.12%, 47.66%, 60.37%, 72.71%, 76.2% and 78.89% with the inclusion of 2.5%, 5%, 7.5%, 10%, 12.5% and 15% rubber sand, respectively, whilst the reduction in the flexural strength was 16.67%, 36.67%, 41.67%, 52.22%, 61.11% and 67.78%, respectively. Pedro et al. (2013) reported a reduction in the compressive strength, flexural strength and modulus of elasticity by partially replacing natural sand in mortars with shredded rubber (size 2–0) mm at levels of 5%, 10% and 15%, by volume. The reduction in the 28 days compressive strength was 9%, 35.31% and 40.28% with the inclusion of 5%, 10% and 15% rubber sand, respectively. The reduction in the modulus of elasticity at the age of 28 days was 11.79%, 28.23% and 31.744% with the inclusion of 5%, 10% and 15% rubber sand, respectively, whilst it was 20.16%, 32.9% and 43.51% at the age of 90 days, respectively.

4.1.2. Replacement levels upto 35%

Turatsinze et al. (2006) partially replaced natural sand (maximum grain size 4 mm) in mortars with shredded non-reusable tyres (maximum grain size 4 mm) at levels of 0%, 20% and 30%, by volume. Fixed w/c ratio and fixed colloidal admixture were used. The results showed a reduction in the compressive strength, tensile strength and elastic modulus with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the 28 days compressive strength was 57.89% and 78.95% with the inclusion of 20% and 30% rubber sand, respectively, whilst the reduction in the 28 days tensile strength was 40% and 70%, respectively. The reduction in the 28 days compressive elastic modulus was 38.37% and 59.16% with the inclusion of 20% and 30% rubber sand, respectively, whilst the reduction in the tensile elastic modulus was 47.25% and 77.59%, respectively. Aules (2011) partially replaced natural sand (maximum size 4.75 mm) in mortars with crumb rubber (maximum size 4.75 mm) at levels ranging from 0% to 30% with an increment of 5%, by volume. Fixed w/c ratio was used. Results showed a reduction in the modulus of elasticity, compressive strength and flexural strength with increasing rubber sand content. The reduction in the compressive strength was approximately 23.81%, 46.02%, 53.97%, 58.73%, 59.52% and 57.93% with the inclusion of 3%, 10%, 15%, 20%, 25% and 30% rubber sand, respectively, whilst the reduction in the flexural strength was approximately 1.3%, 3.91%, 13.17%, 20.5%, 28.94% and 39.48%, respectively. Turatsinze et al. (2007) partially replaced natural sand (maximum size 4 mm) in mortars with rubber (maximum size 4 mm), obtained from shredded non-reusable, at levels of 0%, 20% and 30%, by volume. Fixed w/b ratio, fixed dosage of plasticiser and fixed dosage of stabiliser were used. Results showed a large reduction in the compressive strength, tensile strength and modulus of elasticity with the inclusion of rubber sand. The reduction in the compressive strength was 57.89% and 78.95% with the inclusion of 20% and 30% rubber, respectively, whilst the reduction in the tensile strength was 40% and 66.67%, respectively. The reduction in the compressive elasticity modulus (static elastic modulus) was 38.37% and 59.16% with the inclusion of 20% and 30% rubber, respectively. Similar results were also obtained by Turatsinze et al. (2005).

Correia et al. (2010) reported a reduction in the compressive strength of mortars by replacing part of natural sand (particle size below 2.4 mm) with waste vulcanised rubber scrap particles (size below 1.2 mm) at levels of 10%, 20% and 30%, by weight. At w/c ratio of 0.55, the reduction in the 28 days compressive strength was 34.03%, 48.62% and 48.16% with the inclusion of 10%, 20% and 30%, respectively. Corinaldesi et al. (2011) reported a reduction in the 28 days compressive strength and flexural strength of mortars containing (SBR) or (SR) as natural sand replacement. Natural sand (size 5–0 mm) was partially replaced with either SBR (size 12–0 mm) or SR (size 8–0 mm) at levels of 0%, 10% and 30%, by volume. The reduction in the 28 days compressive strength was approximately 30.12% and 56.63% with the inclusion of 10% and 30% SBR sand, respectively, whilst it was approximately 21.92% and 42.87% with the inclusion of 10% and 30% SR sand, respectively. Nguyen et al. (2010) partially replaced sand in mortars with rubber at levels of 0%, 20% and 30%, by volume. They found a reduction in the 28 days compressive strength, tensile strength and Young's modulus with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the compressive strength was 46.48% and 59% with the inclusion of 20% and 30% rubber sand, respectively, whilst the reduction in the tensile strength was 19.63% and 34.35%, respectively. The reduction in the Young's modulus was 36.51% and 47.3% with the inclusion of 20% and 30% rubber sand, respectively. Sallam et al. (2008) reported a reduction in the compressive strength and splitting tensile strength of concretes by replacing natural sand with crumb rubber (size 5–0.16) at different levels, by volume. The reduction in the 28 days compressive strength was 6.25%, 16.03% and 20.91% with the inclusion of 10%, 20%, 30% rubber sand, respectively, whilst the reduction in the 28 days splitting tensile strength was 14.13%, 28.26% and 41.1%, respectively.

Jingfu and Yongqi (2008) studied flexural strength, at ages of 3, 7 and 28 days, of mortars containing rubber (average size 1.5 mm) as partially natural sand replacement at levels of 0%, 8%, 16%, 21% and 31.2%, by volume. Fixed w/c ratio was used. Results showed a reduction in the flexural strength with the inclusion of rubber sand. The reduction in the 28 days flexural strength was 14.81%, 25.92%, 40.74% and 59.26% with the inclusion of 8%, 16%, 21% and 31.2% rubber sand, respectively. Abdulla and Ahmed (2011) partially replaced natural sand in mortars with crumb rubber (size 2.36–2 mm) at levels ranging from 0% to 30%, by volume. Fixed w/c ratio of 0.4 was used. Results showed a reduction in the compressive strength, modulus of rupture, static modulus of elasticity and dynamic modulus of elasticity with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. In another investigation, Abdulla et al. (2010) partially replaced sand in mortars with crumb rubber (size 2–2.36 mm) at levels ranging from 0% to 35%, by volume. Fixed w/c ratio of 0.3 and fixed dosage of SP were used. They reported that the compressive strength, flexural strength and modulus of elasticity decreased with increasing rubber sand content.

4.1.3. Replacement levels up to 60%

Huang et al. (2013) studied the compressive strength, tensile strength and elastic modulus of ECC containing rubber (size 0.15–0 mm) as partially replacement of iron ore tailings (average size 0.135 mm) that were used as aggregate at levels of 0%, 10%, 20%, 30% and 40%, by volume. Results showed a reduction in the compressive strength, tensile strength and elastic modulus in the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the compressive strength was 63% and 74.14% with the inclusion of 10% and 40% rubber sand. The reduction in the tensile strength was 28.57%, 30.61%, 34.69% and 36.73% with the inclusion of 10%, 20%, 30% and 40% rubber, respectively. Gisbert et al. (2014) reported a reduction in the compressive strength, bending strength, tension strength and Young's modulus of mortars by partially replacing natural sand with crumb rubber at different levels. The reduction in the compressive strength was 63.75%, 71.2%, 77.74% and 90.22% with the inclusion of 10%, 20%, 30% and 40% coarse rubber sand (80% of residue is retained in the size of 2.0 mm), respectively, whilst it was 73.77%, 93.37%, 93.75% and 96.82% with the inclusion of fine rubber sand (80% of residue is retained in the size of 0.25 mm). The reduction in the Young's modulus was 35.27%, 51.51%, 65.97%, 77.33% and 91% with the inclusion of 10%, 15%, 20%, 30% and 40% coarse crumb rubber sand, respectively, whilst it was 55.28%, 71.35%, 92.19%, 96.16% and 97.77%, respectively, with the inclusion of fine rubber sand.

Uygunoğlu and Topçu (2010) reported that partially replacement of natural sand (size 4–0 mm) in self-consolidating mortars with rubber (size 4–1 mm) at levels ranging from 10% to 50%, by weight, decreased the compressive strength, flexural strength and dynamic modulus of elasticity. This reduction increased with increasing rubber sand content. At w/b ratio of 0.4, the reduction in the 28 days compressive strength was approximately 8.36%, 32.72%, 41.41%, 44.9% and 48.38% with the inclusion of 10%, 20%, 30%, 40% and 50% rubber sand, respectively. The reduction in the dynamic modulus of elasticity was 47.4% with the inclusion of 50% rubber sand. Topçu and Sarıdemir (2008) employed two different sizes of rubber (1–0 mm and 4–1 mm) as a part of natural fine aggregate in mortars. Natural sand was partially replaced with rubber at levels of 0%, 10%, 15%, 20%, 30%, 45% and 50%, by volume. They reported a reduction in the compressive strength and flexural strength with the inclusion of rubber sand. This reduction increased as the rubber sand content increased. The reduction in the compressive strength and flexural strength of rubberised mortars was greater in the coarse rubber mortars. Turki et al. (2009) partially replaced natural sand (size 2–0 mm) with rubber made from shredded worn tyres (size 4–1 mm) at levels of 0%, 10%, 20%, 30%, 40% and 50%, by volume. Various w/c ratios were used. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber sand. The reduction in the compressive strength was 20.82%, 24.36%, 42.74%, 65.1% and 79.18% with the inclusion of 10%, 20%, 30%, 40% and 50% rubber sand, respectively, whilst the reduction in the flexural strength was 38.39%, 38.39%, 53.22%, 65.48%, and 63.87%, respectively. Turki et al. (2009) reported a reduction in the static and dynamic elastic Young's modulus values of mortars containing rubber (size 4–1 m, maximum grain size was 3.15 mm) as natural sand (size 2–0 mm) replacement at levels of 10%, 30% and 50%, by volume. The reduction in the static Young's modulus was 60%, 80% and 90.67% with the inclusion of 10%, 20% and 50% rubber sand, respectively, whilst the reduction in the dynamic Young's modulus was 13.21%, 56.49% and 67.44%, respectively. Pierce and Blackwell (2003) partially replaced natural fine aggregate in mortars with crumb rubber (size 0.6 mm) at levels ranging from 32% to 57%, by volume. They reported a reduction in the compressive strength with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. Pelisser et al. (2012) reported a reduction in the compressive strength by replacing natural sand in mortars with recycled tyre rubber (maximum size 2.4 mm) at levels of 0%, 20%, 40% and 60%, by volume. The reduction in the compressive strength increased with increasing rubber sand content (Fig. 5). Eiras et al. (2014) reported a reduction in the compressive strength and flexural strength of mortars by partially replacing natural sand with 40%, 50% and 60% crumb rubber (size ~0.08–1.3 mm), by volume. The reduction in the compressive strength was 77.85%, 79.72% and 88.87% with the inclusion of 40%, 50% and 60% rubber sand, respectively, whilst the reduction in the flexural strength was 76.97%, 79.56% and 88.86%, respectively.

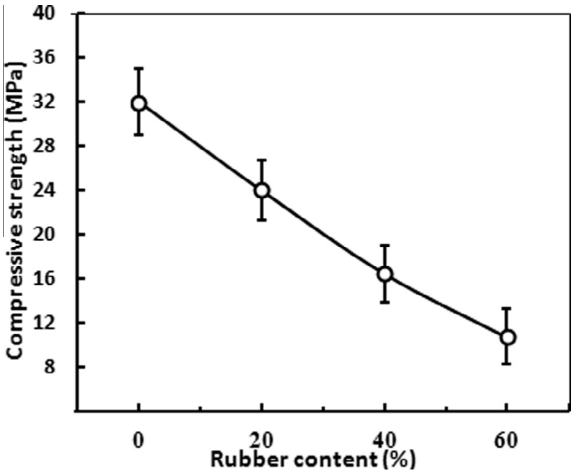

Figure 5. Effect of rubber content on the compressive strength of mortars (Pelisser et al., 2012).

4.2. Rubberised concretes

4.2.1. Replacement levels upto 15%

Skripkiūnas et al. (2007) reported a reduction in the concrete compressive strength, static modulus of elasticity and dynamic modulus of elasticity by 1.46%, 10.82% and 2.47% with the inclusion of 3.2% rubber (size 1–0 mm) as natural sand replacement, by weight, respectively. Holmes et al. (2014) reported a reduction in the compressive strength and Young's modulus of concretes by partially replacing natural sand with crumb rubber (size 4.75–0.425 mm) at a level of 7.5%. On the other hand, the flexural strength increased with the inclusion of rubber sand. They related this enhancement in the flexural strength to the ductile failure of rubber specimens compared to brittle failure of the control. Pelisser et al. (2011) reported 67% and 49% reduction in the 28 days compressive strength and elastic modulus, respectively, of concrete containing 10% recycled tyre rubber (size < 4.8 mm) as natural sand replacement. Chunlin et al. (2011) reported 5.73% and 29.47% reduction in the 28 days compressive and flexural strength, respectively, by partially replacing natural sand in concretes with 10% crumb rubber (size 5–1 mm), by volume. Albano et al. (2005) reported a reduction in the compressive strength and flexural strength by partially replacing natural sand in concretes with recycled rubber from automobile tyre at levels of 5% and 10%, by weight. The reduction in the compressive strength was 61.54% and 88.5% with the inclusion of 5% and 10% rubber sand with a particle size of 0.59 mm, respectively, whilst it was 70.97% and 97.43%, respectively, with a particle size of 0.29 mm. Lijuan et al. (2014) partially replaced natural sand in concretes with rubber at levels of 0%, 2%, 4%, 6%, 8% and 10%, by cement mass. They used different rubber sizes (4, 2, 0.864, 0.535, 0.381, 0.221 and 0.173 mm). They concluded that the inclusion of rubber weakened the axial compressive strength. The axial compressive strength and elastic modulus of the concrete specimens decreased with increasing rubber content and decreasing rubber particle size. Azevedo et al. (2012) partially replaced natural sand in HPCs with tyre rubber waste (dimensions between 2.4 and 1 mm) at levels of 0%, 5%, 10% and 15%, by weight. The compressive strength results at ages of 7 and 28 days decreased with increasing rubber sand content. The reduction in the 28 days compressive strength was approximately 31.53%, 54.36% and 64.63% with the inclusion of 5%, 10% and 15% rubber sand, respectively. Ganesan et al. (2012) reported 15.3%, 14.24% and 22.4% reduction in the 28 days compressive strength of concretes by partially replacement of natural sand with 15% rubber (size < 4.75 mm) when cement content was 277, 339 and 441 kg/m^3, respectively.

Bravo and de Brito (2012) partially replaced natural sand in concretes with rubber aggregate made from used tyres (with the same size of the natural sand) at levels of 0%, 5%, 10% and 15%, by volume. Various w/c ratios were used. The results showed a reduction in the 28 days compressive strength with the inclusion of rubber sand. The compressive strength decreased with increasing rubber sand content. Ghaly and Cahill (2005) partially replaced natural sand in concretes with crumb rubber (size 2–1 mm) at levels of 0%, 5%, 10% and 15%, by volume. Various w/c ratios of 0.47, 0.54 and 0.61 were used. They reported a reduction in the compressive strength with the inclusion of rubber sand. Najim and Hall (2012) reported a reduction in the compressive strength, flexural strength, splitting tensile strength, Young's modulus of elasticity and dynamic modulus of elasticity with the inclusion of crumb rubber (size 6–2 mm) in SCCs as natural sand replacement, by weight. The reduction in the compressive strength was 41.75%, 52.35% and 67.65% with the inclusion of 5%, 10% and 15% rubber sand, respectively. Onuaguluchi and Panesar (2014) partially replaced natural fine aggregate in concretes with crumb rubber (size ~86% smaller 2.3 mm) at levels of 0%, 5%, 10% and 15%, by volume. Fixed w/c ratio and fixed dosage of HRWR were used. Results showed a reduction in the compressive strength, splitting tensile strength and elastic modulus with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the compressive strength was 6.93%, 13.86% and 39.85% with the inclusion of 5%, 10% and 15% rubber sand, respectively, whilst the reduction in the splitting tensile strength was 5.71%, 11.43% and 34.28%, respectively. The reduction in the elastic modulus was 14.51%, 20.21% and 29.27% with the inclusion of 5%, 10% and 15% rubber sand, respectively. Bowland et al. (2012) reported a reduction in the compressive strength of concrete by partially replacing natural sand with ground rubber (maximum size 0.25 mm) at levels of 5%, 10% and 15%, by volume. This reduction increased with increasing rubber sand content.

4.2.2. Replacement levels up to 25%

Guo et al. (2014) reported a reduction in the compressive strength and Young's modulus of concrete mixtures, containing crushed recycled concrete as coarse aggregate, by partially replacing natural sand with crumb rubber (size 1.4–0.85 mm) at levels of 4%, 8%, 14% and 16%, by volume. The reduction in the compressive strength was 4.57%, 23.34%, 26.84% and 30.21% with the inclusion of 4%, 8%, 14% and 16% rubber sand, respectively. Jingfu et al. (2009) partially replaced natural sand in concretes with rubber (size 1.5 mm) at levels of 50, 80, 100 and 120 kg/m^3. The tyre rubber particles were incorporated by replacing the same volume of natural sand. Various w/c ratios and various dosages of plasticiser were used. The results showed a reduction in the compressive strength, tensile elastic modulus and compressive elastic modulus with the inclusion of rubber sand. The reduction in the 28 days compressive strength was 4.37%, 1.46% and 14.56% with the inclusion of 50, 80, 100 and 120 kg/m^3 rubber sand, respectively. On the other hand, the inclusion of rubber sand increased the 28 days flexural strength by 0.25%, 11.31% and 22.36%, respectively. Yi and Fan (2009) reported 8.5% reduction in the ultimate flexural strength by partially replacing natural sand in concretes with 60 kg/m^3 rubber. Parveen et al. (2013) reported a reduction in the compressive strength, flexural strength and splitting tensile strength of concretes by partially replacing natural sand with crumb rubber (size 4.75–0.075 mm) at different levels, by volume. This reduction increased with increasing rubber sand content. The reduction in the compressive strength was 11.05%, 23.48%, 31.49% and 37.29% with the inclusion of 5%, 10%, 15% and 20% rubber sand, respectively. Gesoğlu et al. (2014) partially replaced natural aggregate in concretes with crumb rubber (size either 4 mm or 2 mm) at levels of 0%, 10% and 20%, by total aggregate volume. The results showed a reduction in the compressive strength, splitting tensile strength and modulus of elasticity with the inclusion of rubber aggregate. This reduction increased with increasing rubber aggregate content. The reduction in the compressive strength was 18.94% and 44.1%, respectively, with the inclusion of rubber aggregate (size 4 mm), whilst it was 7.85% and 38.57% with the inclusion of rubber aggregate (size 2 mm). Mohammadi et al. (2014) partially replaced natural sand in concretes with crumb rubber at levels of 0% and 20%, by volume, when w/c ratio was 0.45. There were two cases for the crumb rubber either as received without treatment or after treatment in water-soaking. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber sand at ages of 7, 28 and 56 days. The treated rubberised concrete showed higher strength than the corresponding untreated one. The reduction in the 28 days compressive strength with the inclusion of untreated rubber sand was 51.44%, whilst it was 44.6% for treated rubber sand. Youssf et al. (2014) reported an increase in the compressive strength, tensile strength and modulus of elasticity by partially replacing sand in concretes with 5% and 10% crumb rubber (size 2.36 and 1.18 mm), by volume, whilst the inclusion of 20% rubber sand decreased them. On the other hand, the inclusion of 5%, 10% and 20% rubber (size 2.36–0.15 mm) decreased the compressive strength and the modulus of elasticity. The reduction in the 28 days compressive strength was 18%, 20% and 37% with the inclusion of 5%, 10% and 20% rubber sand. Raj et al. (2011) reported a reduction in the compressive strength, splitting tensile strength and modulus of elasticity by partially replacing natural sand, upto 20% by volume, in SCCs with rubber (maximum size 4.75 mm). This reduction increased as the rubber sand content increased. Balaha et al. (2007) studied the possibility of the usage of ground waste tyre rubber (size < 4 mm) as natural sand replacement in concretes containing different cement contents. Natural sand was partially replaced with rubber at levels of 0%, 5%, 10%, 15% and 20%, by volume. Results showed a reduction in the compressive strength with the inclusion of rubber sand. At cement content of 400 kg/m^3, the reduction in the compressive strength was approximately 6.95%, 12.58%, 18.57% and 28.48% with the inclusion of 5%, 10%, 15% and 20% rubber sand, respectively. Sukontasukkul and Chaikaew (2006) partially replaced natural fine and coarse aggregates with crumb rubber in concrete blocks at levels of 0%, 10% and 20%, by weight. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber aggregate. This reduction increased as the rubber aggregate content increased. Antil et al. (2014) reported 11.1%, 23.54%, 31.85% and 37.39% reduction in the 28 days compressive strength of concretes by partially replacing natural sand with crumb rubber (size 4.75–0.075 mm) at levels of 5%, 10%, 15% and 20%, by volume, respectively. Yung et al. (2013) partially replaced natural sand in SCCs with waste tyre rubber at levels of 0%, 5%, 10%, 15% and 20%, by volume. Two different particle sizes of 0.6 mm and 0.3 mm of the rubber were used. Fixed w/c ratio and fixed dosage of binding agent were used. Results showed a reduction in the 1, 7, 28, 56 and 91 days compressive strength with the inclusion of rubber sand. The reduction in the 28 days compressive strength was 9.67%, 22.39%, 16.12% and 28.9% with the inclusion of 5%, 10%, 15% and 20% rubber sand with a particle size of 0.6 mm, respectively, whilst it was 3.52%, 26.63%, 27.03% and 31.71% with the inclusion of rubber sand with a particle size of 0.3 mm, respectively.

Ganesan et al. (2013) studied the compressive strength, static flexural strength and fatigue flexural strength of rubberised SCCs. Natural sand was partially replaced with rubber (maximum size 4.75 mm) at levels of 15% and 20%, by volume. In fatigue testing, the maximum stress level applied to specimens ranging from 90% to 60% of the static flexural strength. The tests were terminated when the failure of specimens occurred or the number of cycles exceeded 2 million. Results showed a reduction in the compressive strength at ages of 7 and 28 days with the inclusion of rubber sand. The reduction in the 28 days compressive strength was 6.85% and 13.35% with the inclusion of 15% and 20% rubber sand, respectively. On the other hand, the static flexural strength increased with the inclusion of rubber sand. The increment in the static flexural strength was 14.69% and 9.73% with the inclusion of 15% and 20% rubber sand, respectively. This may be due to the better tensile load carrying capacity of rubber particles. The fatigue flexural increased with increasing rubber sand content. The increment in the fatigue flexural was 12.87% and 15.84% with the inclusion of 15% and 20% rubber sand, respectively. They also reported that the static flexural and fatigue flexural can be modified by adding 0.5% and 0.75% steel fibres, by volume. Raj et al. (2011) reported that the average reduction in the compressive strength of SCCs containing rubber (maximum size 4.75 mm) as natural sand replacement at levels of 5%, 10%, 15% and 20%, by volume, was 8%, 16%, 23% and 40%, respectively. The same trend was observed for splitting tensile strength, flexural strength and modulus of elasticity.

Al-Tayeb et al. (2013) reported a reduction in the compressive strength, splitting tensile strength and elastic modulus of concretes containing crumb rubber (size 1 mm) as natural sand replacement at levels of 5%, 10% and 20%, by volume. The reduction in the compressive strength was 5.35%, 14.48% and 20.21% with the inclusion of 5%, 10% and 20% rubber sand, respectively, whilst the reduction in the splitting tensile strength was 11%, 13.69% and 16.67%, respectively. The reduction in the elastic modulus was 8.32%, 15.1% and 22.2% with the inclusion of 5%, 10% and 20% rubber sand, respectively. Thomas et al. (2014) reported a reduction in the compressive strength and flexural strength of concretes containing discarded tyre rubber (40% powder from mesh 30, 35% size 0.8–2 mm and 25% size 2–4 mm) as natural sand replacement up to 20%. The strength decreased with increasing rubber sand content. The reduction in the 28 days compressive strength, at w/c ratio of 0.4, was 3.53%, 11.76%, 12.94%, 21.17%, 29.41%, 41.18%, 94.52% and 52.94%, with the inclusion of 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5% and 20% rubber sand, respectively, whilst the reduction in the 28 days flexural strength was 2.26%, 5.83%, 9.77%, 14.28%, 15.79%, 24.1% and 24.81%, respectively. Güneyisi (2010) reported a reduction in the compressive strength of SCCs containing crumb rubber (similar to the natural sand gradation) as natural sand replacement at levels of 5%, 15% and 25%, by volume. The compressive strength decreased as the rubber sand content increased. Ozbay et al. (2011) reported a reduction in the compressive strength of concrete by partially replacing natural sand with crumb rubber (grain size 3–0 mm) at levels of 5%, 15% and 25%, by volume. The compressive strength decreased with increasing rubber sand content. The reduction in the compressive strength was approximately 4.47%, 10% and 25.98% with the inclusion of 5%, 15% and 25% rubber sand, respectively. Gesoğlu and Güneyisi (2011) partially replaced natural fine aggregate in SCCs with crumb rubber (size < 4 mm) at levels of 0%, 5%, 15% and 25%, by volume. They reported a reduction in the compressive strength with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. Gesoğlu and Güneyisi (2007) reported a reduction in the compressive strength of concretes containing crumb rubber (grading close to the natural fine aggregate) and tyre chips as fine and coarse aggregate replacement, respectively, at levels of 5%, 15% and 25%, by total aggregate volume. This reduction increased as the rubber aggregate content increased. They also reported that the compressive strength can be modified by replacing 10% of cement with silica fume (SF).

4.2.3. Replacement levels up to 33.3%

Rahman et al. (2012) reported a reduction in the compressive strength, dynamic modulus and dynamic shear modulus by partially replacing natural sand in SCCs with rubber (size 4–1 mm) at levels of 0% and 28%, by volume. Grinys et al. (2012) partially replaced natural sand in concretes with crumb rubber (size 2–1 mm) at levels of 0%, 5%, 10%, 20% and 30%, by total aggregate volume. Fixed w/c ratio and fixed dosage of SP were used. Results showed a reduction in the compressive strength and flexural strength with the inclusion of crumb rubber sand. The reduction in the compressive strength was 25%, 37.5%, 65.62% and 82.81% with the inclusion of 5%, 10%, 20% and 30% rubber sand, respectively, whilst the reduction in the flexural strength was 21.42%, 28.35%, 44.53% and 59.63%, respectively. The splitting tensile strength increased by 0.86% and 7.47% with the inclusion of 5% and 10% rubber sand, respectively, whilst it decreased by 11.49% and 49.13% with the inclusion of 20% and 30% rubber sand, respectively. Azmi et al. (2008) reported a reduction in the compressive strength, flexural strength, splitting tensile strength and modulus of elasticity by partially replacing natural sand in concretes with crumb rubber (size 2.35–2 mm) at different levels, by volume. The reduction in the 28 days compressive strength was 8.02%, 13.85%, 27.86% and 50.49% with the inclusion of 10%, 15%, 20% and 30% rubber sand, respectively. The reduction in the 28 days modulus of elasticity was 32.4%, 41.19% and 45.93% with the inclusion of 10%, 15%, 20% and 30% rubber sand, respectively. Grdić et al. (2014) partially replaced natural sand in concretes with crumb rubber (size 4–0.5 mm) at levels of 0%, 10%, 20% and 30%, by volume. Results showed a reduction in the compressive strength, flexural strength and bond strength with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the 28 days compressive strength was 36%, 59.9% and 70.5% with the inclusion of 10%, 20% and 30% rubber sand, respectively, whilst the reduction in the 28 days flexural strength was 20.1%, 34.41% and 55.2%, respectively. The reduction in the 28 days bond strength was 14.6%, 30.4% and 51% with the inclusion of 10%, 20% and 30% rubber sand, respectively. Mohammadi et al. (2014) partially replaced natural sand in concretes with crumb rubber at levels of 0% and 30%, by volume, when w/c ratio was 0.4. There were two cases for the crumb rubber either as received without treatment or after treatment in water-soaking. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber sand at ages of 7, 28 and 56 days. The treated rubberised concrete showed higher strength than the corresponding untreated one. The reduction the 28 days compressive strength with the inclusion of untreated rubber sand was 56.51%, whilst it was 50.95% for treated rubber sand. Hilal (2011) partially replaced natural sand in foamed concretes with crumb rubber (size 5–0.7 mm) at levels of 0%, 20% and 30%, by weight. Results showed a reduction in the compressive strength, splitting tensile strength and flexural strength at ages of 7, 21 and 28 days with the inclusion of rubber sand. The reduction in the 28 days compressive strength was 20.86% and 37.77% with the inclusion of 20% and 30% rubber sand, respectively, whilst the reduction in the splitting tensile strength was 21.93% and 46.45%, respectively. The reduction in the flexural strength was 34.79% and 47.95% with the inclusion of 20% and 30% rubber sand, respectively. Ling (2012) partially replaced natural sand (maximum particle size < 4.75 mm) in concrete paving blocks manufactured with compaction method with crumb rubber (size 3–1 mm and 5–1 mm) at levels of 0%, 10%, 20% and 30%, by volume. Various w/c ratios and fixed dosage of SP were used. Results showed an increase in the compressive strength and modulus of rupture (bending strength “flexural strength”) at replacement level of ~10%. On the other hand, a reduction in the compressive strength and bending strength was obtained at replacement levels of 20% and 30%. The enhancement in the compressive strength and bending strength with the inclusion of 10% rubber sand was 36.65% and 14.16%, respectively. The reduction in the compressive strength was 49.84% and 62.38% with the inclusion of 20% and 30% rubber sand, respectively, whilst the reduction in the bending strength was 28.1% and 44.66%, respectively. Karahan et al. (2012) reported a reduction in the compressive strength, flexural strength, splitting strength and bond strength of SCCs by partially replacing natural sand with crumb rubber (size 4.75–0.15 mm) at levels of 10%, 20% and 30%, by volume. The reduction in the compressive strength was 21.24%, 30.97% and 53.32% with the inclusion of 5%, 10% and 20% rubber sand, respectively, whilst the reduction in the flexural strength was 8.47%, 18.64% and 35.59%, respectively. The reduction in the splitting strength was 5.71%, 11.43% and 22.86% with the inclusion of 5%, 10% and 20% rubber sand, respectively, whilst the reduction in the bond strength was 22.39%, 26.86% and 28.36%, respectively.

Sukontasukkul and Tiamlom (2012) reported a reduction in the compressive strength and elastic modulus of concretes by partially replacing natural sand with rubber at levels of 10%, 20% and 30%, by volume, (Fig. 6). There were two particle sizes of rubber namely large size (passing sieve 6) and small rubber size (passing sieve 26). Specimens containing large rubber size showed higher compressive strength and modulus of elasticity than those containing small rubber size. The reduction in the compressive strength was approximately 42.48%, 65.1% and 78.77% with the inclusion of 10%, 20% and 30% large size rubber sand, respectively, whilst the reduction in the elastic modulus was approximately 17.95%, 33.33% and 53.85%, respectively. Bignozzi and Sandrolini (2006) reported a reduction in the compressive strength and dynamic elastic modulus of SCCs by partially replacing natural sand with 22.2% and 33.3% rubber (size 55% 2–0.5 mm and 45% 0.7–0.5 mm), by volume. The reduction in the 28 days compressive strength was 25.15% and 38.79% with the inclusion of 22.2% and 33.3% rubber sand, respectively, whilst the

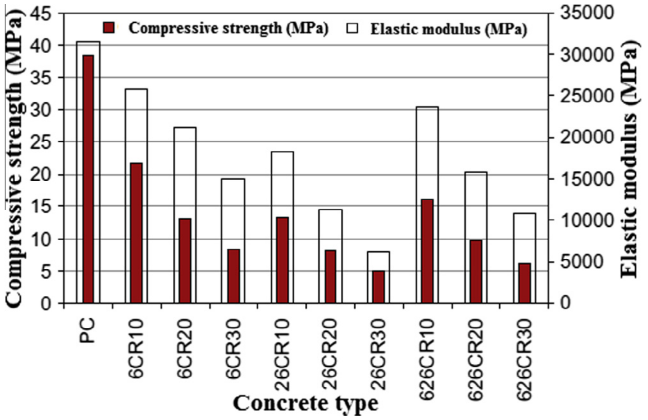

Figure 6. Effect of rubber sand content on compressive strength and elastic modulus of concretes (Sukontasukkul and Tiamlom, 2012).

reduction in the dynamic elastic modulus was 19.39% and 27.57%, respectively.

4.2.4. Replacement levels upto 50%

Valadares et al. (2012) partially replaced natural sand in concretes with shredded rubber (size 4–0 mm) at levels of 0%, 12.5%, 24.15% and 35.77%, by volume. Various w/c ratios were used. Results showed a reduction in the compressive strength, splitting tensile strength and modulus of elasticity with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. The reduction in the 28 days compressive strength was 19.82%, 35.15% and 51.89% with the inclusion of 12.5%, 24.15% and 35.77% rubber sand, respectively, whilst the reduction in the 28 days splitting tensile strength was 23.53%, 38.23% and 44.12%, respectively. The reduction in the 28 days modulus of elasticity was 15.76%, 28.57% and 38.18% with the inclusion of 12.5%, 24.15% and 35.77% rubber sand, respectively. Wang et al. (2013) partially replaced natural sand in CLSRC and CLSRLC with rubber (size 4.75 mm) at levels ranging from 0% to 40%, by volume. Results showed a reduction in the compressive strength with the inclusion of rubber sand. This reduction increased with increasing rubber sand content. For CLSRC, the reduction in the compressive strength was approximately 9.51%, 36.94%, 38.03% and 48.92% with the inclusion of 10%, 20%, 30% and 40% rubber sand, respectively, whilst it was 22.18%, 42.45%, 50.51% and 63.31%, respectively, for CLSRLC. Mohammadi et al. (2014) reported a positive effect of 30% and 40% crumb rubber (treated in water-soaking) as natural sand replacement, by volume, in concretes on fatigue behaviour, whilst 10% and 20% crumb rubber sand showed a negative effect (Fig. 7). Topçu (1995) studied the performance of concrete with rubber (size 1–0 mm and 4–1 mm) aggregate made from used tyres. The proportions of the rubber were between 0% and 45%, by volume. The author observed that the compressive strength at ages of 7 and 28 days did not significantly change below 15% replacement ratio, whilst the mechanical strength worsened for a larger rubber ratio. Mohammed et al. (2012) reported a reduction in compressive strength and splitting tensile strength of hollow concrete blocks by partially replacing natural sand with rubber (size 0.6 mm) at levels of 10%, 25% and 50%, by volume. This reduction increased with increasing rubber sand content.

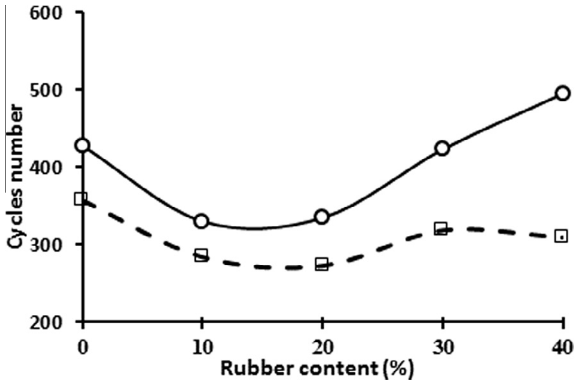

Figure 7. Cycles number before failure versus rubber content (Mohammadi et al., 2014).

Ling (2012) reported a reduction in the compressive strength of concrete blocks at ages of 7 and 28 days by replacing natural sand (size 4 mm) with rubber (size 5–1 mm) at levels ranging from 5% to 50%, by volume. Different w/b ratios of 0.45, 0.5 and 0.55 were used. This reduction increased with increasing rubber sand content. The reduction in the 28 days compressive strength at w/c ratio of 0.45 was 2.27%, 18.83%, 24.35%, 33.77%, 35.39%, 48.7%, 65.91% and 69.165% with the inclusion of 5%, 10%, 15%, 20%, 25%, 30%, 40% and 50% rubber sand, respectively. Güneyisi et al. (2004) reported a reduction in the 90 days compressive strength, splitting tensile strength and modulus of elasticity of concretes containing crumb rubber (maximum particle size 4 mm) as natural fine aggregate replacement and tyre chips (size 40–10 mm) as natural coarse aggregate replacement at levels ranging from 2.5% to 50%, by total aggregate volume. At w/c ratio of 0.6, the reduction in the compressive strength was 12.64%, 22.86%, 40.89%, 54.83%, 69.89% and 86.8% with the inclusion of 2.5%, 5%, 10%, 15%, 25% and 50% rubber aggregate, respectively, whilst the reduction in the splitting tensile strength was 9.68%, 12.9%, 19.35%, 32.26%, 48.39% and 77.42%, respectively. The reduction in the modulus of elasticity was 1.71%, 12.39%, 16.92%, 36.29%, 61.32% and 81.57% with the inclusion of 2.5%, 5%, 10%, 15%, 25% and 50% rubber aggregate, respectively. They also reported that the values of compressive strength, splitting tensile strength and modulus of elasticity can be improved by replacing part of cement with SF (Fig. 8).

4.2.5. Replacement levels upto 100%

Turgut and Yesilata (2008) reported a reduction in the compressive strength, flexural strength and splitting strength of concrete blocks by replacing natural sand with crumb rubber (size 4.75–0.075 mm) at different levels, by

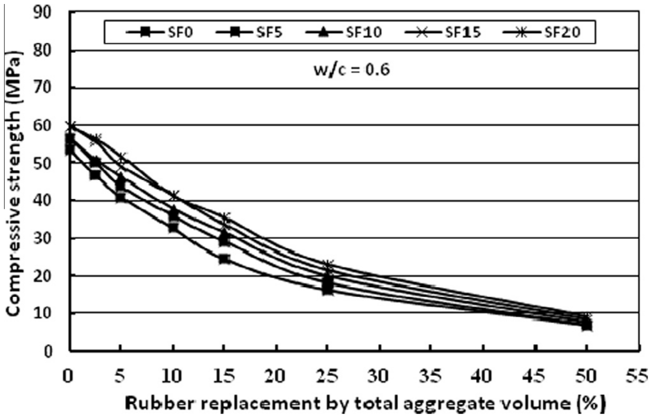

Figure 8. Effect of rubber aggregate content on the compressive strength of concretes.

volume. The reduction in the compressive strength was 12.54%, 33.1%, 57.49%, 69.34%, 81.18% and 84.67% with the inclusion of 10%, 20%, 30%, 40%, 50%, 60% and 70% rubber sand, respectively, whilst the reduction in the splitting strength was 15.17%, 34.48%, 42.41%, 53.1%, 70%, 85.17% and 85.86%, respectively. Issa and Salem (2013) prepared concrete mixtures containing natural sand and crushed sand as fine aggregate (natural sand to crushed sand ratio was 33.33%: 66.66%). Crushed sand was replaced by crumb rubber (size 2.54–0.075 mm) at levels of 0%, 15%, 25%, 50% and 100%, by volume. In addition, all fine aggregate was replaced with crumb rubber at level of 100%, by volume. Fixed w/c ratio and fixed dosage of SP were used. Results showed a reduction in the compressive strength at ages of 7 and 28 days with the inclusion of rubber sand. The reduction in the 28 days compressive strength was 17.85%, 36%, 58.15% and 83.69% by replacing crushed sand at levels of 15%, 25%, 50% and 100%, respectively, whilst it was 96% by replacing full fine aggregate with rubber sand. Taha et al. (2008) reported a reduction in the compressive strength at ages of 7 and 28 days of concretes containing rubber (size 5–1 mm) as natural sand replacement at levels of 25%, 50%, 75% and 100%, by volume. This reduction increased as the rubber sand content increased. The reduction in the 28 days compressive strength was approximately 14.51%, 24.21%, 49.75% and 67.4% with the inclusion of 25%, 50%, 75% and 100% rubber sand, respectively. El-Gammal et al. (2010) replaced natural sand in concretes with crumb rubber (size ∼5–0.2 mm) up to 100%, by weight. Results showed a reduction in the compressive strength with the inclusion of rubber sand. The reduction in the compressive strength was 80.33% and 81.64% with the inclusion of 50% and 100% rubber sand, respectively. Atahan and Yüce (2012) reported a reduction in the compressive strength and elastic modulus of concretes by replacing natural fine aggregate and coarse aggregate with crumb rubber at levels of 0%, 20%, 40%, 60%, 80% and 100%, by volume. This reduction increased with increasing rubber aggregate. The reduction in the compressive strength was approximately 57.96%, 65.61%, 75.8%, 87.26% and 92.35% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber aggregate, respectively.

Khaloo et al. (2008) reported a reduction in the compressive strength and tangential modulus of elasticity of concretes by replacing natural sand (maximum size 4.75 mm) with crumb rubber (maximum size 4.75 mm) at levels of 25%, 50%, 75% and 100%, by volume. The reduction in the compressive strength was 79.33%, 96%, 97.37%, 98.21% with the inclusion of 25%, 50%, 75% and 100% rubber sand, whilst the reduction in the tangential modulus of elasticity was 84.48%, 95.82%, 98.51% and 99.46%, respectively. Batayneh et al. (2008) reported a reduction in the compressive strength, splitting tensile strength and flexural strength of concretes containing rubber (size 4.75–0.15 mm) as natural sand replacement, by volume. The reduction in the compressive strength was 25.15%, 51.56%, 68.14%, 82.35% and 90.13% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber sand, respectively, whilst the reduction in the splitting tensile strength was 34.75%, 47.87%, 66.67%, 81.1% and 92.19%, respectively. The reduction in the flexural strength was 30.7%, 44.56%, 62.5%, 79.1% and 82.61% with the inclusion of 20%, 40%, 60%, 80% and 100% rubber sand, respectively. Khatib and Bayomy (1999) reported a reduction in the 7 and 28 days compressive strength and flexural strength of concretes containing crumb rubber (gradation close to the natural sand) as natural sand replacement. Natural sand was replaced with crumb rubber at levels ranging from 5% to 100%, by volume. Results showed a reduction in the compressive strength and flexural strength with the inclusion of rubber sand. This reduction increased as the rubber sand content increased.

From the above review of the literature in Sections 4.1 and 4.2, it can be noted that the inclusion of rubber sand in the mixture decreased the mechanical strength. This reduction in the mechanical strength may be related to the bond defects between rubber sand and the matrix (Fig. 9) Turatsinze et al., 2006. Corinaldesi et al. (2011)

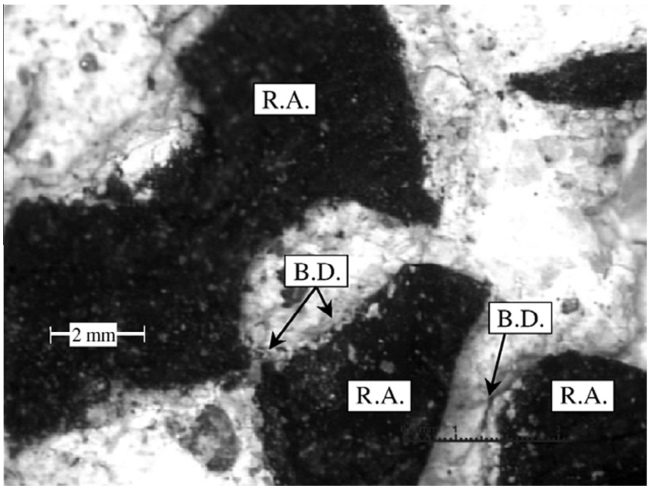

Figure 9. Bond defect (B.D.) between rubber aggregate (R.A.) and cement matrix (Turatsinze et al., 2006).

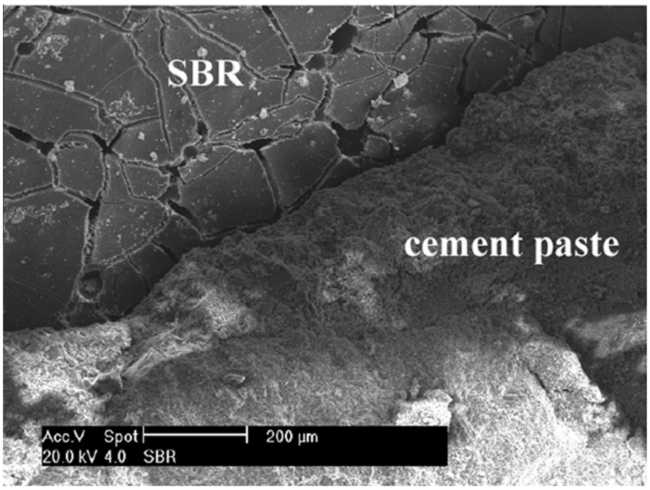

Figure 10. SEM observation of the interfacial zone between cement paste and SBR particles (Corinaldesi et al., 2011).

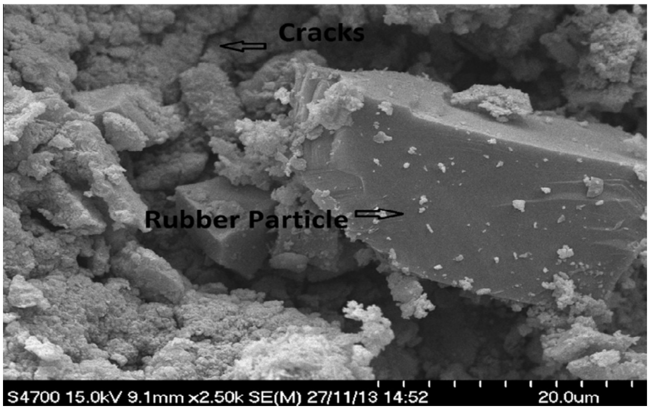

Figure 12. SEM images of rubberised concrete (20% substitution) (Thomas et al., 2014).

related the low strength of rubberised mortar to the low quality of the interfacial transition zone (ITZ) between rubber particles and cement paste (Fig. 10). Turki et al. (2009) related the low strength of rubberised mortar to the void space between rubber aggregate and cement matrix (Fig. 11). Albano et al. (2005) related the low strength to the increased porosity or weakness points in rubberised concrete matrix. Raj et al. (2011) related the low strength of rubberised concrete to the weak interface or the transition zone of the rubberised mortar and the conventional coarse aggregates. These weak interfaces acted as the originators of micro-cracks which eventually grew to macro size, leading to failure under compression. Thomas et al. (2014) related the low strength of rubberised concrete to the smooth surfaces of the rubber particles (Fig. 12) that led to a weak bond with the cement paste. Taha et al. (2008) related the low strength of rubberised concrete to three main reasons: first, the deformability of the rubber particles compared with the surrounding cement paste, that results in initiating cracks around the rubber particles in a fashion similar to that occuring with air voids in normal concrete; second, due to the weak bond between rubber particles and the cement paste; third, due to the possible reduction of the concrete matrix density which depends greatly on the density, size and hardness of the aggregate. Many studies (Ozbay et al., 2011; Karahan et al., 2012; Taha et al., 2008; Khatib and Bayomy, 1999; Eldin and Senouci, 1993; Lee et al., 1998; Chung and Hong, 1999) related the low strength of rubberised mixture to the weak bond between rubber particles and cement paste, and increased matrix porosity. The reduction in the strength by using rubber sand is one of the shortcomings of using this recycled material which limits its wide use by engineers. To alleviate this problem, some studies (Gesoğlu and Güneyisi, 2007; Güneyisi et al., 2004) recommended to replace part of cement with SF to mitigate the degradation in strength caused by rubber sand. Others (Bowland et al., 2012) recommended to mix rubber particles with latex before they are added to the concrete/mortar aiming to improve the strength. However, few studies have proposed to improve the rubber-cementitious matrix bond (Li et al., 1998), notably treating the rubber particles with NaOH aqueous solution (Segre and Joekes, 2000). However, the results that they obtained showed that the strength benefit due to the rubber treatment was small.

5. Impact energy and impact load

Taha et al. (2008) replaced natural sand in concretes with rubber (size 5–1 mm) at levels of 25%, 50%, 75% and 100%, by volume. They reported that the impact

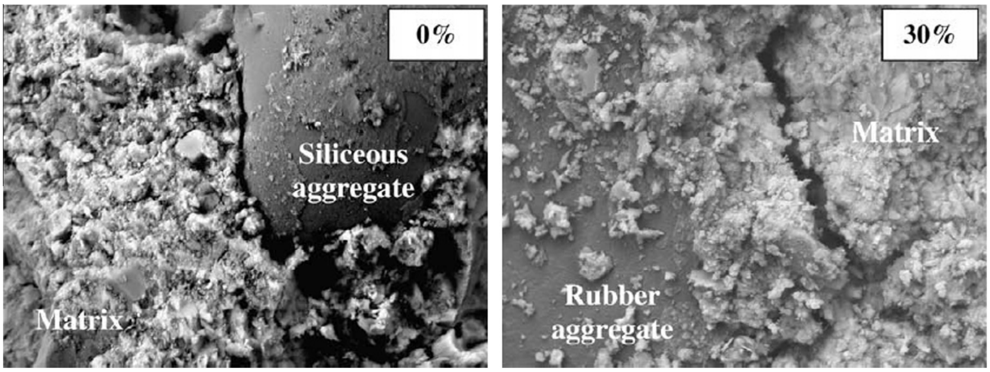

Figure 11. Adherence of ITZ of rubber-free and rubber aggregate mortar with 30% of substituted rubber aggregate (Turki et al., 2009).

energy improved with the inclusion of rubber sand up to 50%. A further increase in the rubber sand content beyond this level led to a reduction in the impact strength. Sallam et al. (2008) partially replaced natural sand in concretes with crumb rubber (size 5–0.16 mm) at levels of 10%, 20% and 30%, by volume. They reported that the presence of crumb rubber increased the resistance of concrete to crack initiation under the impact load. Al-Tayeb et al. (2013) reported that the inclusion of crumb rubber (size 1 mm) in concretes at levels of 5%, 10% and 20%, by volume, as natural sand replacement improved the impact load behaviour. They also reported an increase in the fracture energy (static test) of concretes with the inclusion of rubber sand. The enhancement in the fracture energy was 34.61%, 38.46% and 46.15% with the inclusion of 5%, 10% and 20% rubber sand, respectively. Maher et al. (2013) partially replaced natural sand in concrete beams with crumb rubber (specific area 0.0266 m^2/g) at levels of 0%, 5%, 10% and 20%, by volume. Fixed w/c ratio was used. They reported that the impact tup load, inertial load and bending load of concrete increased with increasing rubber sand content, whilst static peak bending decreased. The fracture energy increased with increasing rubber sand content. Gesoğlu et al. (2014) partially replaced natural aggregate in concretes with crumb rubber (size either 4 mm or 2 mm) at levels of 0%, 10% and 20%, by total aggregate volume. Results showed an increase in the fracture energy with the inclusion of rubber aggregate (size 4 mm). The fracture energy increased by 1.38 and 1.33 times greater with the inclusion of 10% and 20% rubber aggregate, respectively. On the other hand, the inclusion of 10% and 20% rubber aggregate with a size of 2 mm decreased fracture energy by 26.2% and 18.5%, respectively. Pedro et al. (2013) partially replaced natural sand in mortars with shredded rubber (size 2–0 mm) at levels of 5%, 10% and 15%, by volume. They reported that the inclusion of rubber sand improved impact behaviour in which crack width decreased. Vadivel et al. (2014) reported an improvement in the impact resistance of concrete specimens by partially replacing natural sand with 6% rubber (size ~4.75–0.1 mm), by weight.

Atahan and Yüce (2012) replaced natural fine aggregate and coarse aggregate in concretes with crumb rubber at levels of 0%, 20%, 40%, 60%, 80% and 100%, by volume. Results showed that the maximum impact load decreased with increasing rubber aggregate content. The inclusion of 100% rubber showed 71.6% maximum load lower than that of the control. The total time of impact increased with increasing rubber aggregate content. Over 600% difference in impact time was achieved with 100% rubber aggregate. Sukontasukkul et al. (2013) partially replaced natural sand in concrete panels with rubber at levels of 25% and 50%, by volume fractions. They reported that rubberised concrete panels can absorb impact energy from the bullets and reduce the damage.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture, upto 50%, improved impact energy. Rubber sand, upto 20% improved impact load behaviour. The improvement in the impact energy and impact load of concrete with the inclusion of rubber sand is one advantage of using this recycled material.

6. Toughness

Sukontasukkul and Chaikaew (2006) reported an increase in the toughness with the inclusion of rubber as natural fine aggregate and coarse aggregate replacement. Najim and Hall (2012) partially replaced natural sand in SCCs with crumb rubber (size 6–2 mm) at levels of 0%, 5%, 10% and 15%, by weight. They reported that there was a general tendency for all crumb rubber aggregate replacements to significantly increase all toughness indices (I_5, I_{10} and I_{20}). The increase in I_5 was 53.94%, 16.97% and 33.64% with the inclusion of 5%, 10% and 15% rubber sand, respectively, whilst the increase in I_{20} was 117.84%, 53.28% and 102.58%, respectively. The inclusion of 5% rubber showed the highest toughness. Liu et al. (2013) partially replaces natural sand (maximum size 5 mm) in concretes with recycled tyre rubber (grain size 2 mm) at levels of 0%, 5%, 10% and 15%, by volume. They reported that concrete toughness increased with increasing rubber sand content. The ratio of the flexural strength to the compressive strength of rubber concretes with 5%, 10% and 15% rubber was 1.08, 1.16 and 1.26 times greater than the plain concrete, respectively. This indicated that rubber concrete is better in anti-cracking performance than the plain concrete. Balaha et al. (2007) reported that concrete containing ground waste tyre rubber (size < 4 mm) as a partial replacement of natural sand had much more toughness than concrete without rubber sand. The damping ratio of the rubberised concrete containing 20% rubber sand was much higher than that of normal concrete by approximately 63.2%. Taha et al. (2008) replaced natural sand in concrete with crumb rubber (size 5–1 mm) at levels of 25%, 50%, 75% and 100%, by volume. They reported that fracture toughness of concretes increased with the inclusion of rubber sand.

Khaloo et al. (2008) reported a maximum increase in the toughness with the inclusion of 25% rubber (maximum size 4.75 mm), by total aggregate volume. Beyond this level, the toughness decreased due to the systematic reduction in strength (Fig. 13). Guo et al. (2014) partially replaced natural sand in concretes, containing recycled coarse aggregate, with crumb rubber (size 1.4–0.85 mm) at levels of 0%, 4%, 8%, 12% and 16%, by volume. Results showed that as the rubber sand content increased from 4% to 16%, the fracture toughness first increased and then decreased with increasing rubber sand content. The inclusion of 4% and 8% rubber sand exhibited the highest fracture toughness. On the other hand, Huang et al. (2013) partially replaced iron ore tailings (IOTs) that used as aggregates in ECC with rubber (average size 0.135 mm) at levels of 0%, 10%, 20%, 30% and 40%, by volume. They reported that the

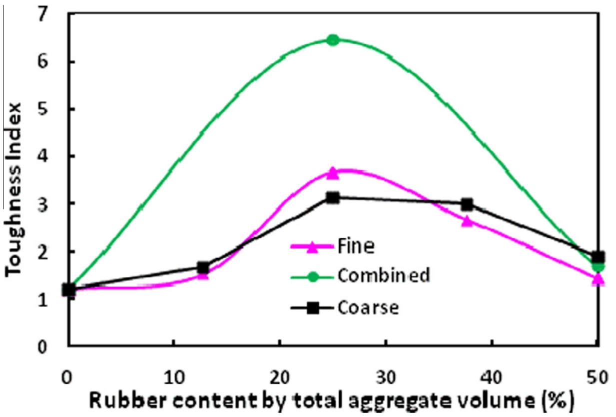

Figure 13. Effect of rubber aggregate content on the toughness index values (Khaloo et al., 2008).

rubber particles led to a substantial reduction in fracture toughness by about 50% compared to the control. This reduction may be related to increasing porosity of ECC with tyre rubber content which weakens the matrix. The weak interfacial bond between tyre rubber particles and surrounding cement paste allowed a crack to easily develop around the tyre rubber particles. Table 5 summarises the mentioned studies about the effect of rubber sand on the toughness of mortars and concretes.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture increased the toughness of concrete as reported by many studies. The increase of the fracture toughness of concrete with the inclusion of rubber particles can be explained by the ability of the rubber to add a few toughening mechanisms to the conventional concrete including crack bridging by rubber particles and rubber particles' bending, compressing and twisting. The tyre rubber particles absorb part of the energy the matrix is subjected to, and therefore the composite material can absorb more energy before fracturing compared to the bare concrete matrix (Taha et al., 2008). The enhancement in the toughness of concrete with the inclusion of rubber sand is one advantage of using this recycled material.

7. Ductility and strain capacity

Guo et al. (2014) reported that appropriate rubber content increased the ductility of the concrete mixtures, but too much rubber may have a negative effect on the ductility. Jingfu and Yongqi (2008) reported that rubberised mortar and concrete specimens exhibited ductile failure and significant deformation before fracture. The ultimate deformations of both rubberised mortar and concrete specimens increased more than 2–4 times that of control specimens. Grdić et al. (2014) reported an increase in the concrete ductility by partially replacing natural sand with crumb rubber (size 4–0.5 mm) at levels of 10%, 20% and 30%, by volume. The ductility index increased with increasing rubber sand content. The increment in the ductility index was 25%, 81.25% and 93.75% with the inclusion of 10%, 20% and 30% rubber sand, respectively. Hilal (2011) report that foamed concretes containing 20% and 30% crumb rubber (size 5–0.7 mm) as natural sand replacement, by weight, showed a cohesive behaviour at failure than the control. Vadivel et al. (2014) reported an improvement in the ductility of concrete by partially replacing natural sand with 6% rubber (size ~4.75–0.1 mm), by weight. Lijuan et al. (2014) partially replaced natural sand in concretes with rubber at levels of 0%, 2%, 4%, 6%, 8% and 10%, by cement mass. They used different rubber sizes (4, 2, 0.864, 0.535, 0.381, 0.221 and 0.173 mm). They reported that the inclusion of rubber in the concrete specimens can improve the deformability. Thus, the ultimate strain of normal concrete increased. The ultimate strain of rubberised concretes increased as rubber content enlarged and particle size dwindled. Issa and Salem (2013) reported that the inclusion of rubber as natural sand replacement in concrete enhanced its ductility and damping properties. Mohammed, 2010) partially replaced natural sand in concrete slabs with crumb rubber (size 0.6 mm) at levels of 0% and 10%, by volume. Results showed that the rubberised slabs achieved the ductility requirements of the Eurocode 4, whilst the conventional concrete slabs were considered as brittle composite slabs. Ganesan et al. (2013) partially replaced natural sand in concrete of beam-column joints with rubber (maximum size 4.75 mm) at levels of 0% and 15%, by volume. They reported that the addition of shredded rubber sand could bring about improvement in the beam-column joint behaviour under cyclic loads in term of ductility. They also showed that the brittleness values index of rubber concrete specimens reduced by 16% compared to the control. Najim and Hall (2012) reported higher ductility and energy absorption

Table 5
Effect of rubber sand on the toughness of mortars and concretes.

References	Rubber content (%)	Size (mm)	Increased toughness
Najim and Hall (2012)	5, 10 and 15	6–2	√
Liu et al. (2013)	5, 10 and 15	Maximum 5	√
Balaha et al. (2007)	20	<4	√
Taha et al. (2008)	25, 50, 75 and 100	5–1	√
Khaloo et al. (2008)	25	Maximum 4.75	√
Khaloo et al. (2008)	75 and 100	Maximum 4.75	×
Guo et al. (2014)	4 and 8	1.4–0.85	√
Guo et al. (2014)	16	1.4–0.85	×
Huang et al. (2013)	10, 20, 30 and 40	Average 0.135	×

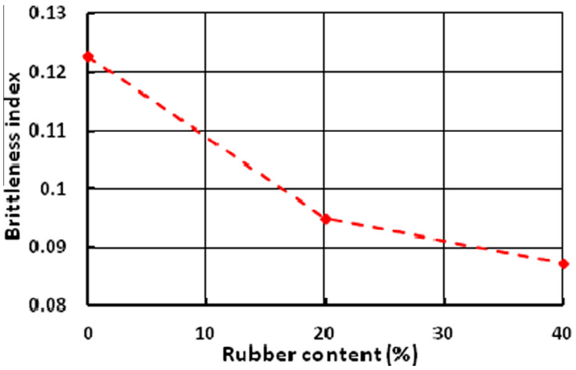

Figure 14. Effect of rubber sand content on the brittleness index (Ho et al., 2012)

of SCCs containing crumb rubber (size 6–2 mm) as natural sand replacement at levels of 5%, 10% and 15%, by weight. Raj et al. (2011) reported lower value of brittleness index of SCCs containing rubber (maximum size 4.75 mm) as partial replacement of natural sand at levels of 5%, 10%, 15% and 20%, by volume.

Ling (2012) reported that concretes containing 10%, 20% and 30% rubber as natural sand replacement, by volume, did not demonstrate brittle failure, but ductile failure. Aules (2011) reported that the inclusion of rubber (maximum size 4.75 mm) in mortar as natural sand replacement up to 30% increased its ductility. Li et al. (2011) partially replaced natural sand in concretes encased by FRP with crumb rubber (size 160 μm) at levels of 0%, 15% and 30%, by volume. They reported that the FRP encased rubberised concretes had higher confinement effectiveness and higher ductility than FRP confined conventional plain concrete. FRP tube encased rubberised concrete cylinders might be a viable alternative for energy absorbing cylinders. Ho et al. (2012) partially replaced natural sand (size 4–0 mm) in concretes with rubber (size 4–0 mm) at levels of 0%, 20%, 30% and 40%, by volume. Fixed w/c ratio and various dosages of SP were used. Results showed a reduction in the brittleness and damage with increasing rubber sand content (Fig. 14). The rubberised concretes exhibited elastic quality index values within acceptable limits for the design of cement-based pavements. Mohammadi et al. (2014) partially replaced natural sand in concrete with crumb rubber (after treatment in water-soaking). They reported that the failure of rubberised concrete samples was found to be gradual without a total sudden collapse or a major crack. Rubberised concrete samples could hold themselves even after the occurrence of failure cracks without shattering to pieces (Fig. 15). Topçu (1995) replaced natural sand in concretes with rubber (size 1–0 and 4–1 mm) at levels ranging from 0% to 45%, by volume. They reported that the ductility of concrete improved with the inclusion of rubber sand. Pierce and Blackwell (2003) reported an improvement in the ductility of mortars by replacing natural fine aggregate with crumb rubber (size 0.6 mm) at levels ranging from 32% to 57%, by volume. Khaloo et al. (2008) replaced natural sand (maximum size 4.75 mm) in concretes with rubber at levels of 25%, 50%, 75% and 100%, by volume. They found more ductile behaviour in rubberised concretes compared to the plain concrete under compression.

Turatsinze et al. (2006) reported that the inclusion of shredded non-reusable tyres (maximum size 4 mm) in mortars as natural sand replacement at levels of 0%, 20% and 30%, by volume, limited the cement-based mortars brittleness and increased their strain capacity. Nguyen et al. (2010) reported that the strain capacity before macro-cracking location was improved by partially replacing natural sand in mortars with rubber at levels of 20% and 30%, by volumes. Huang et al. (2013) reported that the tensile strain capacity of ECC containing rubber as partial replacement of iron ore tailings that were used as aggregate, by volume, increased with increasing rubber content. The increase in the tensile strain capacity was 11.11%, 16.67%, 44.44% and 66.67% with the inclusion of 10%, 20%, 30% and 40% rubber sand, respectively. This means that the incorporation of tyre rubber aggregate is beneficial to the performance of ECC in terms of tensile ductility.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture increased its ductility. The failure state in rubberised concretes did not occur quickly and did not cause any detachment in the specimens compared to the control (Khaloo et al., 2008). As reported by Raj et al. (2011) the addition of rubber sand in concretes reduced the brittleness index value and improved the ductility of concretes, thus

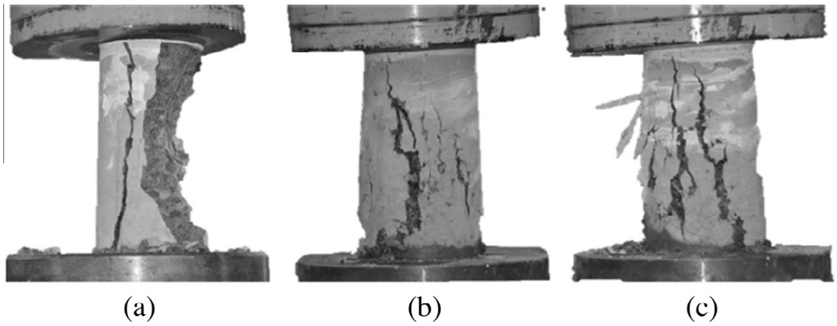
(a) (b) (c)

Figure 15. Effect of rubber sand on concrete cracking failure (a) no rubber sand, (b) 20% rubber sand and (c) 40% rubber sand Mohammadi et al. (2014).

enabling a transition from a brittle material to a ductile one. This is due to the better energy absorption capacity of rubber, which led to plastic deformations at the time of fracture. Li et al. (2011) related the enhancement in the ductility of rubberized concrete to the incorporation of small ductile particles into concrete. At the same line, the inclusion of rubber aggregate in the matrix increased its strain capacity as reported by Turatsinze et al. (2006), Nguyen et al. (2010) and Huang et al. (2013). The enhancement in the ductility of concrete with the inclusion of rubber sand is one advantage of using this recycled material.

8. Shrinkage

Jingfu et al. (2009) partially replaced natural sand in concretes with rubber (size 1.5 mm) at levels of 50, 80, 100 and 120 kg/m^3. The tyre rubber particles were incorporated by replacing the same volume of natural sand. Results showed higher drying shrinkage with the inclusion of rubber sand. The drying shrinkage increased with increasing rubber sand content. Turatsinze et al. (2006) reported that the inclusion of shredded non-reusable tyers (maximum size 4 mm) in mortars at levels of 20% and 30%, by volume, increased the free shrinkage. Bravo and de Brito (2012) found an increase in the shrinkage by partially replacing natural sand in concretes with rubber (with the same size of the natural sand) made from used tyres at levels of 0%, 5%, 10% and 15%, by volume. The shrinkage increased by 43% at 15% rubber sand content. Pedro et al. (2013) reported an increase in the shrinkage of mortar specimens by partially replacing natural sand with 15% shredded rubber (size 2–0 mm), by volume. Yung et al. (2013) measured the change in the length of concrete prisms containing waste tyre rubber as natural sand replacement. Natural sand was partially replaced with rubber at levels of 0%, 5%, 10% and 20%, by volume. Fixed w/c ratio and fixed dosage of binding agent were used. There are three different particle sizes of rubber (0.6, 0.3 and 0.6 + 0.3 mm). Results showed an increase in the shrinkage with increasing rubber sand content and rubber fineness. The change in the length at 28 days was −0.0183% for the control, whilst it was −0.0294%, −0.0298% and −0.0308% for the specimens containing 5% rubber sand with particle size of 0.6, 0.3 and 0.6 + 0.3 mm, respectively. The average change in the length of the rubber specimens was –0.0248%, which was 35% higher than that of the control. When 20% waste tyre rubber powder was added, the change was the largest, and the average change in the length of rubber specimens was 95% higher than that of the control.

Sukontasukkul and Tiamlom (2012) partially replaced natural sand in concretes with two different particle sizes of rubber at levels of 0%, 10%, 20% and 30%, by volume. The sizes of crumb rubber were No. 6 (passing sieve No. 6) and No. 26 (passing sieve No. 26). Results showed an increase in the drying (free) shrinkage with increasing rubber sand content. Specimens containing a small size of rubber sand showed higher free shrinkage than those containing large size. Turatsinze et al. (2007, 2005) found an increase in the free shrinkage by partially replacing natural sand in mortars with 20% and 30%, by volume, with rubber (maximum size 4 mm) obtained from shredded non-reusable (Fig. 16). Huang et al. (2013) reported an increase in the drying shrinkage of ECC by partially replacing iron ore tailings (average size 0.135 mm), that were used as aggregate, with tyre rubber (size 0.15–0 mm) at levels of 10%, 20%, 30% and 40%, by volume. The drying shrinkage increased as the rubber sand content increased. The drying shrinkage increased about 1.5 times for specimens containing 40% tyre rubber aggregate compared to the control.

Uygunoğlu and Topçu (2010) reported an increase in the drying shrinkage of self-consolidating mortars by partially replacing natural sand with tyre rubber (size 4–1 mm) at levels of 10%, 20%, 30%, 40% and 50%, by weight, when w/c ratio was 0.4. At w/c ratio of 0.51, the inclusion of rubber at levels of 10%, 20% and 30% reduced the drying shrinkage, whilst levels of 40% and 50% significantly increased it. Aules (2011) reported a reduction in the length change of mortars by partially replacing natural sand with rubber (maximum size 4.75 mm) up to 30%, by volume. This reduction increased as the rubber sand content decreased. Chunlin et al. (2011) reported lower shrinkage of concretes by partially replacing natural sand with 10% crumb rubber (size 5–1 mm), by volume. Table 6 summarises the mentioned studies about the effect of rubber sand on the shrinkage of mortars and concretes.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture increased the shrinkage as reported by several studies. The higher shrinkage of rubberised mortar/concrete is partly due to the lower compressive strength and elastic modulus. At the same line, Turatsinze et al. (2006) reported that the benefit of the higher straining capacity of rubberised cement-based composites could be offset by their higher shrinkage length change. However, the shrinkage of rubberised mortar/concrete seemed to be depending on the particle size and the content of rubber sand in the mix-

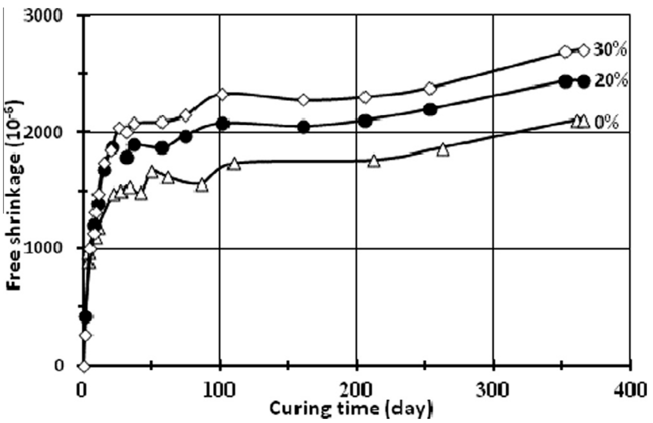

Figure 16. Effect of rubber sand content on the free shrinkage of mortar specimens (Turatsinze et al., 2007).

Table 6
Effect of rubber sand on the shrinkage of mortars and concretes.

References	Rubber content (%)	Size (mm)	Increased shrinkage
Turatsinze et al. (2006)	20 and 30	Maximum 4	√
Bravo and de Brito (2012)	5, 10 and 15	Same sand size	√
Pedro et al. (2013)	15	2–0	√
Yung et al. (2013)	5, 10 and 20	0.6, 0.3 and 0.6 + 0.3	√
Sukontasukkul and Tiamlom (2012)	10, 20 and 30	Sieve No. 6 and No. 26	√
Turatsinze et al. (2007, 2005)	20 and 30	Maximum 4	√
Huang et al. (2013)	10, 20, 30 and 40	0.15–0	√
Uygunoğlu and Topçu (2010)	10, 20, 30, 40 and 50	4–1	√ (w/c = 0.4)
Uygunoğlu and Topçu (2010)	10, 20 and 30	4–1	√ (w/c = 0.51)
Uygunoğlu and Topçu (2010)	40 and 50	4–1	× (w/c = 0.51)
Aules (2011)	Up to 30	Maximum 4.75	×
Chunlin et al. (2011)	10	5–1	×

ture. In terms of rubber sand content, the shrinkage increased with increasing rubber sand content in which rubber sand is weaker and highly flexible than natural sand. As the replacement rate increased, the lack of fine aggregate caused a greater decrease of internal restraints and led to higher shrinkage (Sukontasukkul and Tiamlom, 2012). In terms of rubber sand particle size, the smaller size appeared to shrink much more than the larger size (Sukontasukkul and Tiamlom, 2012). Sukontasukkul and Tiamlom (2012) reported that large shrinkage might come from two combined effects: (1) the lower internal restraint (from lack of sand) and (2) the increase of more flexible material. Uygunoğlu and Topçu (2010) reported that the increase in the total shrinkage with the inclusion of rubber sand is a consequence of the increase of open porosity and thus shrinkage increases. The enhancement in the drying shrinkage of mortar/concrete with the inclusion of rubber sand is one advantage of using this recycled material.

9. Abrasion resistance

Ozbay et al. (2011) reported a reduction in the abrasion resistance of concretes by partially replacing natural sand with crumb rubber (size 3–0 mm) at levels of 5%, 15% and 25%, by volume. The abrasion resistance decreased with increasing rubber sand content. The increase in the depth of wear was approximately 11.59%, 17.39% and 23.19% with the inclusion of 5%, 15% and 25% rubber, respectively. Sukontasukkul and Chaikaew (2006) partially replaced natural fine and coarse aggregates in concrete blocks with crumb rubber at levels of 0%, 10% and 20%, by weight. They reported that skid resistance increased with the inclusion of rubber aggregate. The skid resistance increased with increasing rubber aggregate content. Ganesan et al. (2012) reported 20% increase in the abrasion resistance of concrete by partially replacing natural sand with 15% rubber (size < 4.75 mm), by weight. Thomas et al. (2014) partially replaced natural sand in concretes with discarded tyre rubber (40% powder from mesh 30, 35% size 2–0.8 mm and 25% size 4–2 mm) upto 20% at different w/c ratios. They reported that the rubberised concrete exhibited better resistance to abrasion than the control when w/c ratios were 0.4 and 0.5. At w/c ratio of 0.45, the inclusion of rubber up to 7.5% showed less abrasion resistance than the control, whilst better abrasion resistance was obtained for the remaining mixtures (i.e. rubber sand > 7.5%). Grdić et al. (2014) reported an increase in the abrasion resistance of concrete by partially replacing natural sand with crumb rubber (size 4–0.5 mm) at a level of 10%, by volume. On the other hand, the inclusion of 20% and 30% rubber sand decreased it. Valadares et al. (2012) reported an increase in the abrasion resistance of concretes containing 12.5%, 24.15% and 35.77% shredded rubber (size 4–0 mm) as natural sand replacement, by volume. The abrasion resistance increased with increasing rubber sand content. The abrasion wear depth of the control was 2.6 mm, whilst it was 2.0, 1.5 and 1.1 mm with the inclusion of 12.5%, 24.15% and 35.77% rubber sand, respectively.

From the mentioned studies in this section, it can be noted that the abrasion resistance of concrete with the inclusion of rubber sand still needs more investigations. Although there are contradictory reports about the effect of rubber sand on abrasion resistance, it can be concluded that rubber sand can increase the abrasion resistance if appropriate rubber sand content and suitable w/c ratio were used.

10. Freeze/thaw and ageing resistance

Paine et al. (2012) studied the performance of rubberised concrete aggregate under freeze/thaw cycles. They found that the incorporation of rubber aggregate improved the resistance of freeze/thaw cycles. Paine and Dhir (2010) reported that concrete containing 4% rubber with different particle sizes of 1.5–0.5, 8–2 and 25–5 mm as natural sand replacement provided good resistance to freeze-thaw.

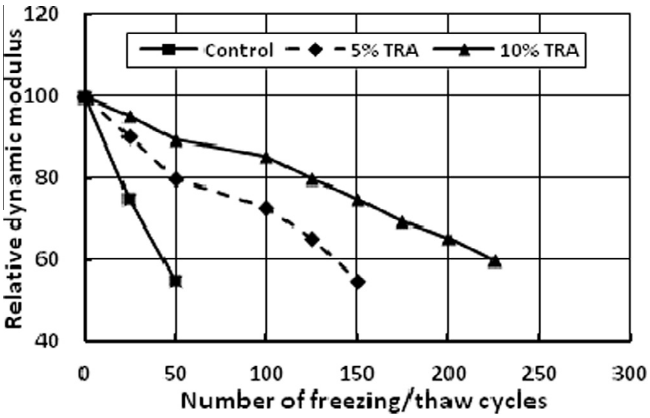

Figure 17. Effect of rubber ash content on the variation of relative dynamic modulus with a number of freezing and thawing cycles (Al-Akhras and Samadi, 2004).

Al-Akhras and Samadi (2004) reported higher freeze/thaw resistance of mortars containing rubber ash (size 0.15 mm) as natural sand replacement at levels of 5% and 10%, by weight. Increasing rubber ash sand content led to increasing freeze/thaw resistance (Fig. 17). Topçu and Demir (2007) exposed concrete specimens containing rubber (size 4–1 mm) as natural sand replacement at levels of 10%, 20% and 30%, by volume, with 30 freeze-thaw cycles according to ASTM C 666. Results showed that the damage as a result of freeze-thaw in concrete containing 10% rubber sand was less than the damage in the control. In spite of the reduction in concrete strength because of the increase in rubber ratio, an increase was observed in durability against freeze-thaw of the 10% rubber concrete. Karahan et al. (2012) partially replaced natural sand in SCCs with rubber (size 4.75–0.15 mm) at levels of 0%, 10%, 20% and 30%, by volume. They exposed concrete specimens to 300 freeze/thaw cycles. Results showed a slight reduction in the flexural strength after freeze/thaw cycles with the inclusion of 10% rubber sand compared to the control. The reduction in the flexural strength was 6.78% and 5.56% with the inclusion of 0% and 10% rubber sand, respectively. On the other hand, the inclusion of 20% and 30% rubber sand led to a significant reduction in the flexural strength after freeze/thaw cycles. This reduction reached 12.5% and 13.16% with the inclusion of 20% and 30% rubber sand, respectively. Turgut and Yesilata (2008) reported higher freeze-thaw resistance of concrete blocks containing crumb rubber (size 4.75–0.075 mm) as natural sand replacement at levels exceeding 50%, by volume. Pedro et al. (2013) partially replaced natural sand in mortars with 15% shredded rubber (size 2–0 mm), by volume. They tested the specimens under accelerated ageing at 112 days according to En 1015-21. They reported that mortar specimens containing rubber sand are not particularly susceptible to weathering.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture increased its freeze/thaw resistance. The freeze/thaw resistance increased with increasing rubber sand content. The rubberised concrete had better resistance to freeze/thaw cycles than the control due to the incorporation of air in the matrix caused by the addition of rubber. The enhancement in the freezing/thaw of concrete with the inclusion of rubber sand is one advantage of using this recycled material.

11. Fire resistance and thermal insulation

Topçu and Demir (2007) reported a reduction in the residual compressive strength after firing at 150, 300 and 400 °C for 3 h of mortars containing rubber (size 4–1 mm) as natural sand replacement at levels of 10%, 20% and 30%, by volume. The reduction in the residual compressive strength increased with increasing rubber sand content. Guo et al. (2014) reported a reduction in the residual compressive strength and Young's modulus of concretes by partially replacing natural sand with crumb rubber (1.4–0.85 mm) at levels of 4%, 8%, 14% and 16%, by volume, after firing at 200, 400 and 600 °C for 2 h. The residual compressive strength decreased with increasing rubber sand content. On the other hand, the inclusion of rubber sand reduced the micro-crack results by elevated temperatures. The number of micro-cracks decreased with increasing rubber sand content. In fact, crumb rubber helped to alleviate the initiation and development of cracks in concrete under the effect of elevated temperatures. This may be due to the fact that the rubber is melted under approximately 170 °C, providing space for the evaporated water in concrete to escape from the concrete, thus significantly reducing the pore pressure caused by the water vapour, one of the main reasons leading to the cracking of concrete under higher temperature (Netinger et al., 2011). At the same line, the inclusion of an appropriate amount of rubber sand in concrete improved its energy absorption capacity (toughness) after exposure to elevated temperatures.

Marques et al. (2013) partially replaced natural aggregates in concretes with shredded rubber at levels of 0%, 5%, 10% and 15%, by volume. The specimens were exposed to 400, 600 and 800 °C for 1 h accordance with ISO 834. Results showed a reduction in the residual compressive strength and residual splitting tensile strength after exposure to elevated temperatures. This reduction increased with increasing rubber aggregate content. At 400 °C, the reduction in the compressive strength was 24%, 39.8% and 54.8% with the inclusion of 5%, 10% and 15% rubber aggregate, respectively, compared to the control specimen heated at the same temperature. At 800 °C, the reduction in the compressive strength was 37.3%, 55.4% and 69.5% with the inclusion of 5%, 10% and 15% rubber aggregate, respectively. The reduction in the splitting tensile strength at 400 °C was 5.7%, 20.9% and 37.7% with the inclusion of 5%, 10% and 15% rubber aggregate, respectively, compared to the control specimen heated at the same temperature. At 800 °C, the reduction in the splitting tensile strength was 47.9%, 57.1% and 63.6% with the inclusion of 5%, 10% and 15% rubber aggregate, respectively. They also reported that the relative reduction in the rubberised concrete should not prevent it from being used in structural applications. Correia et al. (2012) partially replaced natural aggregates in concretes with shredded rubber at levels of 0%, 5%, 10% and 15%, by volume. They reported that higher rubber content and increasing heat flux led to a worse fire reaction response particularly in terms of ignition time, heat release rate and smoke production.

Paine et al. (2012) reported that the inclusion of rubber in concrete as natural sand replacement decreased its thermal conductivity. Issa and Salem (2013) reported that the inclusion of crumb rubber (size 2.54–0.075 mm) as natural sand replacement in concrete enhanced its insulation properties. As the rubber sand content in the concrete increased, the thermal conductivity decreased. Paine and Dhir (2010) reported lower thermal conductivity, and lower U-value of concrete containing rubber (sizes of 1.5–0.5, 8–2 and 25–5 mm) as natural sand replacement. Mohammed et al. (2012) reported lower thermal conductivity of rubberised hollow concrete blocks compared to normal hollow blocks, of which the thermal conductivity of crumb rubber (size 0.6 mm) particles (0.16 W/m K) is lower than that of natural sand (1.5 W/m K) (Fig. 18). Hall et al. (2012) partially replaced natural sand (size 5 mm) in concretes with crumb rubber (size 6–2 mm) at levels of 0%, 10%, 20% and 30%, by weight. They reported that the substitution of natural sand with rubber appeared to cause a significant reduction in thermal conductivity. Sukontasukkul (2009) reported 20–50% reduction in the thermal conductivity of concretes by partially replacing sand with 10–30% crumb rubber, by volume. The sizes of crumb rubber were No. 6 (passing sieve No. 6) and No. 26 (passing sieve No. 26). Results showed that the crumb rubber concretes exhibited lower heat transfer rate and higher heat resistivity than the plain concrete. The reduction in the heat transfer was 16.58%, 44.45% and 54.62% with the inclusion of 10%, 20% and 30% rubber sand with large size (passing sieve No. 6), respectively, whilst it was 45.38%, 48.22% and 49.73%, respectively, with the inclusion of small size rubber sand (passing sieve No. 26). In addition, crumb rubber concretes showed lower thermal conductivity compared to the control. The thermal conductivity of the plain concrete was 0.531 W/m K, the K-values of crumb rubber concretes were lower by approximately 20–50% and in the range of 0.241–0.443 W/m K (Fig. 19). Pelisser et al. (2012) reported 13.8% reduction in the thermal conductivity of mortar containing 40% recycled tyre rubber (maximum size 2.4 mm) as natural sand replacement, by volume, compared to the control. Fadiel et al. (2014) reported 13.1%, 15.2%, 17% and 21.2% reduction in the thermal conductivity of mortar specimens containing 10%, 20%, 30% and 40% crumb rubber (size 0.6–0 mm), respectively, as natural sand replacement, by weight. 18.2%, 24.6%, 26% and 27.8% reduction in the thermal conductivity was obtained with the inclusion of 10%, 20%, 30% and 40% crumb rubber (size 2–0.84 mm), respectively. Eiras et al. (2014) reported lower thermal conductivity of mortars containing 40%, 50% and 60% crumb rubber (size ~0.08–1.3 mm) as natural sand replacement, by volume. The thermal conductivity decreased with increasing rubber sand content. Pierce and Blackwell (2003) concluded that mortars containing crumb rubber (size 0.6 mm) as natural fine aggregate replacement at levels ranging from 32% to 57%, by volume, showed higher thermal insulation.

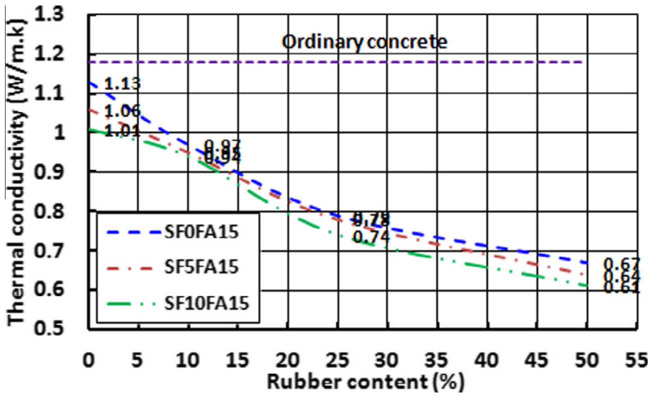

Figure 18. Effect of rubber sand content on the thermal conductivity of concrete block specimens at 28 days air curing (Mohammed et al., 2012).

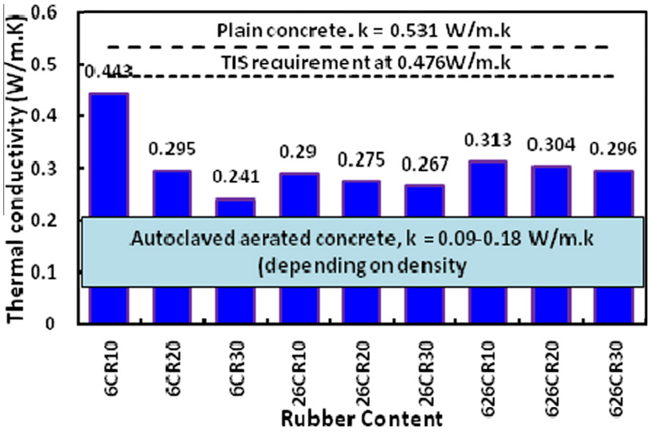

Figure 19. Effect of rubber content and fineness of the thermal conductivity of concretes (Sukontasukkul, 2009).

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture decreased its thermal conductivity. This means that the inclusion of rubber sand in the mixture increased its thermal insulation. The thermal insulation increased with increasing rubber sand content. Theoretically, the thermal conductivity is proportional inversely to the density of the material. Since crumb rubber concrete is lower in density, it should be expected to exhibit a lower value of thermal conductivity (Sukontasukkul, 2009). The reduction in the thermal conductivity of the rubberised matrix could be partly attributed to increasing air entrapment caused by non-wetting rubber particles during mixing and partly to the lower thermal conductivity of the crumb rubber particles. As the addition of crumb rubber increased, there was a greater moisture-dependent effect on the saturated state thermal conductivity due to the increase apparent porosity caused by air entrapment (Hall et al., 2012). Increasing thermal insulation of mortar/concrete with the inclusion of rubber sand is one advantage of using this recycled material. It can be used as construction material where thermal insulation is required. On the other hand, the inclusion of rubber sand in the mixture decreased its fire resistance, but decreased the risk of spalling caused by exposure to elevated temperatures.

12. Carbonation resistance

Bravo and de Brito (2012) reported a reduction in the carbonation resistance of concrete specimens containing rubber aggregate made from used tyres (with the same size of the natural sand) as natural sand replacement at levels of 5%, 10% and 15%, by volume. The carbonation depth slightly increased with increasing rubber sand content. The increase in the carbonation depth may be due to the greater void volume between rubber aggregate and the cement paste.

It can be clearly noted that there is a distinct lack in studying the effect of rubber sand on the carbonation resistance of mortar/concrete. Indeed the carbonation resistance of mortar/concrete containing rubber sand still needs more investigations. This can be a major topic for future investigations. However, according to the available study, it can be concluded that the inclusion of rubber sand in the matrix decreased its carbonation resistance. This one disadvantage of the disadvantages of using this recycled material.

13. Corrosion resistance

Karahan et al. (2012) reported that reinforcing bar mass loss of concrete without rubber and concrete containing 10% crumb rubber (size 4.75–0.15 mm) as natural sand replacement, by volume, was almost the same. On the other hand, when crumb rubber content reached 30%, the reinforcing bar mass loss was approximately two times greater than the control concrete. Yung et al. (2013) reported that partially replacing natural sand in concretes with 5% rubber (size 0.6 or 0.3 mm), by volume, led to anti-sulphate corrosion resistance.

It can be clearly noted that there is a distinct lack in studying the effect of rubber sand on the corrosion resistance. The corrosion resistance of bar imbedded in mortar/concrete containing rubber sand still needs more investigations. This can be a major topic for future investigations.

14. Water absorption, porosity and chloride ion penetration

Segre et al. (2004) studied the percentage of water absorption of mortars containing 10% rubber (size 0.2 mm) as natural sand replacement, by weight. The results showed lower percentage of water absorption with the inclusion of rubber sand. Marques et al. (2008) reported a reduction in the percentage of water absorption at ages of 7, 28, 56 and 90 days by partially replacing 12% natural sand with rubber (passed in sieve 0.8 mm), by volume. The reduction in the percentage of water absorption with the inclusion of rubber sand was approximately 5.55%, 7.4%, 23.43% and 6.34% at ages of 7, 28, 56 and 90 days, respectively. Pedro et al. (2013) reported 8.9% reduction in the water absorption of mortar specimens, tested at age of 28 days, with the inclusion of 5% shredded rubber (size 2–0 mm) as natural sand replacement, by volume. On the other hand, it increased by 6.93% with the inclusion of 10% rubber sand. The inclusion of 15% rubber showed comparable water absorption to the control. They also reported that the inclusion of 15% rubber sand led to better permeability performance. Ganesan et al. (2012) reported a reduction in the water permeability, percentage of water absorption and chloride ion penetration of concrete by partially replacing natural sand with rubber (size < 4.75 mm), by weight. Gesoğlu et al. (2014) reported a reduction in the permeability of concrete specimens with the inclusion of rubber (size either 4 mm or 2 mm) as natural aggregate replacement at levels of 10% and 20%, by total aggregate volume. The inclusion of 10% and 20% rubber sand with particle size of 4 mm reduced the permeability coefficient by 43.75% and 67.46%, respectively, whilst the inclusion of rubber sand with particle size of 2 mm reduced it by 40.73% and 43.1%, respectively. Ling (2012) found a reduction in the concrete porosity by partially replacing natural sand with 10% rubber, by volume. On the other hand, partially replacing natural sand with 20% and 30% rubber, by volume, led to an increase in the porosity of concretes. Sukontasukkul and Tiamlom (2012) reported a reduction in the absorption of concrete specimens containing small rubber size (passing sieve 26). The reduction in the absorption was 30.77%, 15.38% and 11.54% with the inclusion of 10%, 20% and 30% small size rubber sand, by volume, respectively. On the other hand, concrete specimens containing large rubber size (passing sieve 6) showed an increase in the absorption. The increase in the absorption was approximately 11.54%, 21.15% and 34.62% with the inclusion of 10%, 20% and 30% large size rubber sand, by volume, respectively. Hilal (2011) reported an increase in the percentage of water absorption in foamed concretes by partially replacing natural sand with crumb rubber (size 5–0.7 mm) at levels of 20% and 30%, by weight. The increment in the percentage of water absorption at age of 28 days was 10.32% and 22.15% with the inclusion of 20% and 30% rubber sand, respectively.

Azevedo et al. (2012) studied the capillary water absorption coefficient of HPCs containing tyre waste rubber. They reported an increase in the capillary water absorption coefficient by partially replacing natural sand with tyre rubber (dimensions between 2.4 and 1 mm), by weight. The increase in the capillary water absorption coefficient was

71.43%, 85.71% and 95.24% with the inclusion of 5%, 10% and 15% rubber sand, respectively. Bravo and de Brito (2012) reported an increase in the percentage of water absorption with the inclusion of rubber aggregate made from used tyres (with the same size of the natural sand) as natural sand replacement. The percentage of water absorption increased with increasing rubber sand content. The increment in the percentage of water absorption was approximately 2.86%, 12.99% and 14.29% with the inclusion of 5%, 10% and 15% rubber sand, respectively. The inclusion of 5% rubber sand led to a reduction in chloride diffusion, whilst an increase in the chloride diffusion coefficient occurred when the replacement ratio increased from 5% to 15%. Onuaguluchi and Panesar (2014) reported an increase in the water absorption and porosity of concrete mixtures by partially replacing natural sand with crumb rubber (size ~86% smaller than 2.3 mm) at levels of 5%, 10% and 15%, by volume. The water absorption and porosity increased with increasing rubber sand content. Thomas et al. (2014) reported an increase in the rate of water absorption of concrete mixtures by partially replacing natural sand with discarded tyre rubber (40% powder from mesh 30, 35% size 2–0.8 mm and 25% size 4–2 mm) up to 20%. Bignozzi and Sandrolini (2006) reported an increase in the percentage of water absorption of SCCs, at age of 28 days, containing rubber (size 55% 2–0.5 mm and 45% 0.7–0.5 mm) as natural sand replacement at levels of 22.2% and 33.3%, by volume. The increase in the percentage of water absorption was 4% and 10.67% with the inclusion of 22.2% and 33.3% rubber sand, respectively.

Karahan et al. (2012) reported an increase in the porosity and water absorption of SCCs containing 10%, 20% and 30% rubber (size 4.75–0.15 mm) as natural sand replacement, by volume. The increment in the porosity was 5%, 6% and 12% with the inclusion of 10%, 20% and 30% rubber sand, respectively, whilst the increment in the percentage of water absorption was 10%, 14% and 29%, respectively. Fadiel et al. (2014) reported 24% and 4% reduction in the water absorption of mortar specimens by replacing natural sand with crumb rubber (size 0.6–0 mm) at levels of 10% and 20%, by volume, respectively, whilst 30% and 40% rubber sand increased it by 4.5% and 67%, respectively. They also reported that the inclusion of 10%, 20% and 30% rubber (size 2–0.84 mm) in mortar specimens as natural sand replacement decreased the water absorption by 32.5%, 25% and 6%, respectively, whilst the inclusion of 40% rubber (size 2–0.84) increased it by 10%. Mohammed et al. (2012) reported an increase in the water absorption by partially replacing natural sand in hollow concrete blocks with crumb rubber (size 0.6 mm) at levels of 10%, 25% and 50%, by volume. The water absorption increased with increasing rubber sand content. Eiras et al. (2014) reported higher percentage of absorption by partially replacing natural sand in mortars with crumb rubber (size ~1.3–0.08 mm) at levels of 40%, 50% and 60%, by volume. Turgut and Yesilata (2008) reported an increase in the water absorption and porosity of concrete blocks containing crumb rubber (size 4.75–0.075 mm) as natural sand replacement at different levels, by volume. The increment in the water absorption was 24.92%, 52.13%, 63.93%, 95.1%, 112.46%, 121,97% and 142.95% with the inclusion of 10%, 20%, 30%, 40%, 50%, 60% and 70% rubber sand, respectively, whilst the increment in the porosity was 21.21%, 42.42%, 46.97%, 65.15%, 69.79%, 65.15% and 72.73%, respectively. Turki et al. (2009) partially replaced natural sand (size 2–0 mm) with rubber made from shredded worm tyres (size 4–1 mm) up to 50%, by volume. They reported an increase in the porosity with the inclusion of rubber sand. The porosity increased with increasing rubber sand content. The increment in the total porosity (by pycnometer method) was 76.51%, 262.12% and 471.21% with the inclusion of 10%, 30% and 50% rubber sand, respectively, whilst it was 12.89%, 24.32% and 87.18% (by an image analysis), respectively. Uygunoğlu and Topçu (2010) reported higher percentage of apparent porosity and water absorption in self-consolidating mortars containing scrap tyre rubber (size 4–1 mm) as natural sand (size 4–0 mm) replacement, by weight. Natural sand was partially replaced with rubber sand at levels ranging from 10% to 50%. Various w/c ratios were used. The percentage of apparent porosity and water absorption increased with the inclusion of rubber sand. They increased with increasing rubber sand content (Fig. 20). At w/b ratio of 0.4, the inclusion of 50% rubber increased the percentage of water absorption by 71.4% compared to the control.

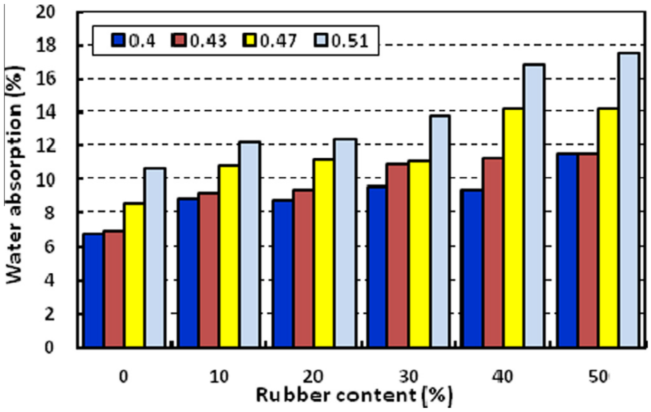

Figure 20. Effect of rubber sand content on the water absorption of self-consolidating mortars (Uygunoğlu and Topçu, 2010).

Gesoğlu and Güneyisi (2011) partially replaced natural fine aggregate in SCCs with crumb rubber (size < 4 mm) at levels of 0%, 5%, 15% and 25%, by volume. Results showed that the percentage of water absorption and chloride ion permeability of SCCs increased with the inclusion of rubber sand. As the rubber sand content increased from 0% to 25%, the chloride ion penetration increased from 2491 to 3460 Coulombs and from 2131–3139 Coulombs at ages of 28 and 90 days, respectively. The increase in the percentage of water absorption at age of 28 days was approximately 5.81%, 15.32% and 35.77% with the inclusion of 5%, 15% and 25% rubber sand, respectively.

Table 7
Effect of rubber sand on the water absorption, porosity and chloride ion penetration of mortars and concretes.

References	Rubber content (%)	Size (mm)	Effect
Segre et al. (2004)	10	0.2	– Reduced water absorption
Marques et al. (2008)	12	Passing sieve 0.8	– Reduced water absorption
Pedro et al. (2013)	5, 10 and 15	2–0	– 5% reduced water absorption – 10% increased water absorption – 15% better permeability
Ganesan et al. (2012)	15	<4.75	– Reduced water permeability, water absorption and chloride ion penetration
Gesoğlu et al. (2014)	10 and 20	4 and 2	– Reduced permeability coefficient
Ling (2012)	10, 20 and 30	3–31 and 5–1	– 10% reduced porosity – 20% and 30% increased porosity
Sukontasukkul and Tiamlom (2012)	10, 20 and 30	Passing sieve No. 26	– Reduced water absorption
Sukontasukkul and Tiamlom (2012)	10, 20 and 30	Passing sieve No. 6	– Increased water absorption
Hilal, (2011)	10 and 20	5–0.7	– Increased water absorption
Azevedo et al. (2012)	5, 10 and 15	2.4–1	– Increased capillary water absorption
Bravo and de Brito (2012)	5, 10 and 15	Similar to sand gradation	– Increased water absorption
Onuaguluchi and Panesar (2014)	5, 10 and 15	~86% smaller than 2.3 mm	– Increased water absorption and porosity
Thomas et al. (2014)	2.5–20%	Mesh 30, 2–0.8 mm, 4–2 mm	– Increased water absorption
(Bignozzi and Sandrolini (2006)	22.2 and 33.3	55% 2–0.5 and 45% 0.7–0.5	– Increased water absorption
Karahan et al. (2012)	10, 20 and 30	4.75–0.15	– Increased porosity
Fadiel et al. (2014)	10, 20, 30 and 40	0.6–0	– 10%, 20% decreased water absorption – 30%, 40% increased water absorption
Fadiel et al. (2014)	10, 20, 30 and 40	2–0.84	– 10%, 20%, 30% decreased water absorption – 40% increased water absorption
Mohammed et al. (2012)	10, 25 and 50	0.6	– Increased water absorption
Eiras et al. (2014)	40, 50 and 60	~1.3–0.08	– Increased water absorption
Turgut and Yesilata (2008)	10–70	4.75–0.075	– Increased water absorption and porosity
Turki et al. (2009)	10, 30 and 50	4–1	– Increased porosity
Uygunoğlu and Topçu (2010)	10–50	4–1	– Increased water absorption and porosity
Gesoğlu and Güneyisi (2011)	5, 15 and 25	<4	– Increased chloride ion permeability
Al-Akhras and Samadi (2004)	5 and 10	0.15	– Reduced chloride ion penetration
Oikonomou and Mavridou, (2009)	2.5, 5, 7.5, 10, 12.5 and 15	1.18–0.75	– Reduced chloride ion penetration depth
Onuaguluchi and Panesar (2014)	5, 10 and 15	~86% smaller than 2.3 mm	– Reduced RCPT
Gesoğlu and Güneyisi (2007)	5, 15 and 25	Similar to sand gradation	– Increased chloride ion penetration depth

They also reported that these values of chloride ion permeability and percentage of water absorption can be lowered by replacing part of cement with fly ash (FA). Al-Akhras and Samadi (2004) measured the resistance to chloride ion penetration of mortars in terms of the electrical charge passed through the specimens in Coulombs according to ASTM C1202-97. Natural sand was partially replaced with rubber ash (size 0.15 mm) at levels of 0%, 5% and 10%, by weight. The control mortar showed the highest value of electrical charge. The electrical charge passed through the specimens containing 5% and 10% rubber ash sand reduced by 27.18% and 86.88%, respectively. Oikonomou and Mavridou (2009) reported a reduction in the chloride ion penetration depth by partially replacing natural sand in mortars with worn automobile tyre rubber (size 1.18–0.75 mm) at different levels, by weight. This reduction was 14.22%, 16.76%, 25.43%, 30.25%, 35.18% and 35.85% with the inclusion of 2.5%, 5%, 7.5%, 10%, 12.5% and 15% rubber, respectively. Onuaguluchi and Panesar (2014) reported a reduction in the rapid chloride permeability (RCPT) of concrete specimens by partially replacing 5%, 10% and 15% of natural fine aggregate with crumb rubber (size ~86% smaller 2.3 mm), by volume. Gesoğlu and Güneyisi (2007) reported an increased in the chloride penetration depth of concretes containing crumb rubber (grading close to the natural fine aggregate) and tyre chips as replacement of natural fine and coarse aggregate, respectively, at levels of 5%, 15% and 25%, by total aggregate volume. The increment in the chloride depth increased as the content of rubber aggregate increased. They also reported that the chloride penetration depth can be reduced by replacing 10% cement with SF. Table 7 summarises the mentioned studies about the effect of rubber sand on the water absorption, porosity and chloride ion penetration of mortars and concretes.

From the above review of the literature in this section, it can be noted that the inclusion of rubber sand in the mixture increased its percentage of water absorption and porosity, as reported by several studies, but it mainly depended on the rubber particle size and its content in the matrix. In general, the cause of high absorption could be the result of the formation of porosity during mixing process. As known, rubber particles are non-polar by nature (water insolvable), during mixing, they are able to trap air bubbles at the particle surfaces (Fig. 21). This phenomenon causes the interface between cement paste and rubber to be porous and highly absorptive. On the other hand, small particle size of rubber (size < 0.5 mm) reduced the absorption. This is because the smaller particles of rubber acts as fillers to fill up capillary pores in the matrix that

Figure 21. trapped air bubbles at rubber passing sieve No. 6 (Sukontasukkul and Tiamlom, 2012).

lead the absorption to be lower (Sukontasukkul and Tiamlom, 2012). Karahan et al. (2012) reported that the reason behind the increased capacity could be related to the higher amounts of air were trapped during mixing (Bignozzi and Sandrolini, 2006), a factor that may have occurred due to the tendency of rubber particles to entrap air in their rough surfaces because of their nonpolar nature (Turatsinze and Garros, 2008; Benazzouk et al., 2007) and/or because the hydrophobic nature of rubber increases air content when rubber particles are added. Uygunoğlu and Topçu (2010) related the reduction in the absorption to the entrapment of air by the rubber particles at the particle-paste and particle-particle interfaces. Gesoğlu and Güneyisi, 2011) related the increase in the absorption with increasing rubber content to the increase in porosity of rubber in mixtures and probably due to some deviations of rubber particles from sand grain size distribution and/or a significant higher air amount trapped during mixing procedure of rubberised mixtures. The increase in the water absorption of the mortar/concrete with the inclusion of rubber sand is one disadvantage of the disadvantages of using this recycled material. On the other hand, Ling (2012) reported that as a small proportion (~10%) of rubber was distorted and filled the voids between the solid particles (natural aggregate) under a compression force of a plant-made machine. This filling mechanism was found to reduce the porosity by filling up the free pore volume in the concrete mixture. The chloride ion penetration depth increased with increasing rubber sand content. However, the magnitudes of the chloride penetration depth can be reduced by replacing 10% cement with SF (Gesoğlu and Güneyisi, 2007) or by replacing part of cement with FA (Gesoğlu and Güneyisi, 2011, 2011).

15. Resistance to aggressive environmental

Segre et al. (2004) studied the durability of mortar containing 10% rubber (size 0.2 mm) as natural sand replacement, by weight, exposed to 5% HCl for 6 days. Results showed higher resistance of rubber mortar against HCl compared to the control. Topçu and Demir (2007) prepared mortar specimens by partially replacing natural sand with crumb rubber (size 1–0 mm or 4–1 mm) at levels of 10%, 20%, 30% and 40%, by volume. Some specimens were cured in NaCl solution simulating the effect of seawater. Other specimens were kept in normal curing for 28 days. Results showed a reduction in the dynamic elasticity modulus with the inclusion of rubber. The reduction in the dynamic elasticity modulus was 35%, 50%, 60% and 74% with the inclusion 10%, 20%, 30% and 40% rubber sand (size 1–0 mm), respectively, whilst it was 20%, 31%, 50% and 63%, respectively, with the inclusion of rubber sand with a particle size of 4–1 mm. Azevedo et al. (2012) studied the resistance of HPCs containing tyre waste rubber as natural sand replacement at levels of 0%, 5%, 10% and 15%, by weight, against sulphuric acid attack. After curing for 56 days, the specimens were exposed to sulphuric acid for a period of 28 days. Results showed that increasing rubber sand content led to higher mass loss degree (Fig. 22). Ganesan et al. (2012) reported that the weight loss of concrete specimens containing 15% rubber sand (size < 4.75 mm) after exposure to seawater or acidic solution (H_2SO_4) or sulfuric acid for 90 days was less than the control.

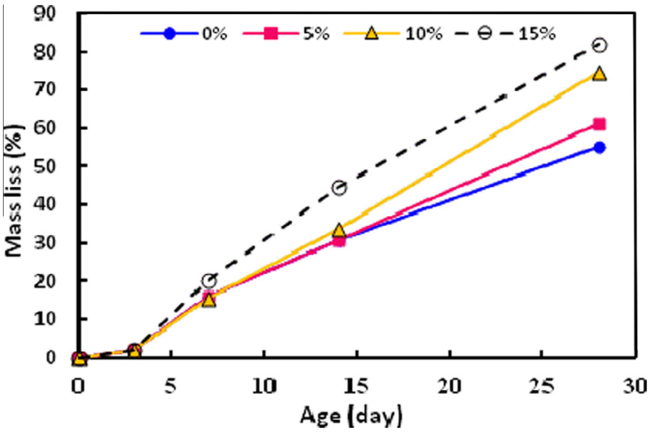

Figure 22. Effect of rubber sand content on the mass loss after sulfuric acid attack of concretes (Azevedo et al., 2012).

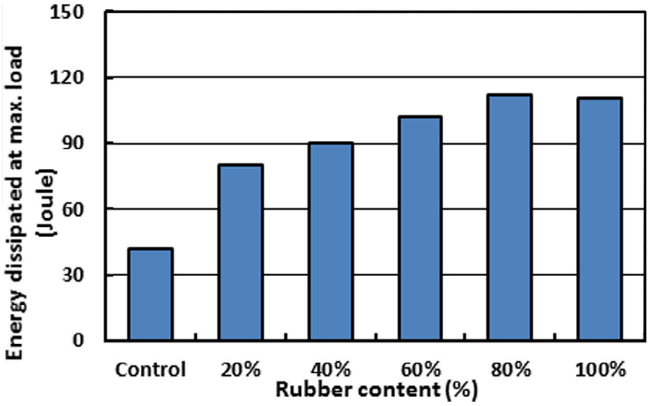

Figure 23. Effect of rubber aggregate content on the average energy transferred at maximum load of concretes (Atahan and Yüce, 2012).

From the above mentioned studies in this section, it can be clearly noted that there is a distinct lack of studying the effect of aggressive environmental resistance on mortar/concrete containing rubber sand. The aggressive environmental resistance of mortar/concrete containing rubber sand still needs more investigations. This can be a major topic for future investigations. However, according to the available studies, it can be noted that the inclusion of rubber sand in the matrix increased its resistance against HCl and seawater.

16. Energy absorption

Ganesan et al. (2013) partially replaced natural sand in concrete of beam-column joints with rubber (maximum size 4.75 mm) at levels of 0% and 15%, by volume. They reported that the addition of shredded rubber sand could bring about improvement in the beam-column joint behaviour under cyclic loads in term of the energy absorption capacity. Ozbay et al. (2011) reported an enhancement in the energy absorption of concretes by partially replacing natural sand with crumb rubber (size 3–0 mm) at levels of 5%, 15% and 25%, by volume. The energy absorption increased with increasing rubber sand content. The enhancement in the energy absorption was approximately 3.42%, 11.98% and 25.66% with the inclusion of 5%, 15% and 25% rubber sand, respectively. Atahan and Yüce (2012) replaced natural fine aggregate and coarse aggregate in concretes with crumb rubber at levels of 0%, 20%, 40%, 60%, 80% and 100%, by volume. The small rubber particles that were used to replace natural sand passed mesh sizes of 10 and 20, whilst large particles passed through a 13 mm screen that was used to replace the natural coarse aggregate. They reported that the energy dissipated by the rubber concrete specimens at maximum load increased drastically as rubber aggregate content increased (Fig. 23). A maximum of 160.8% increment was measured between the control specimen and the 100% rubber specimen.

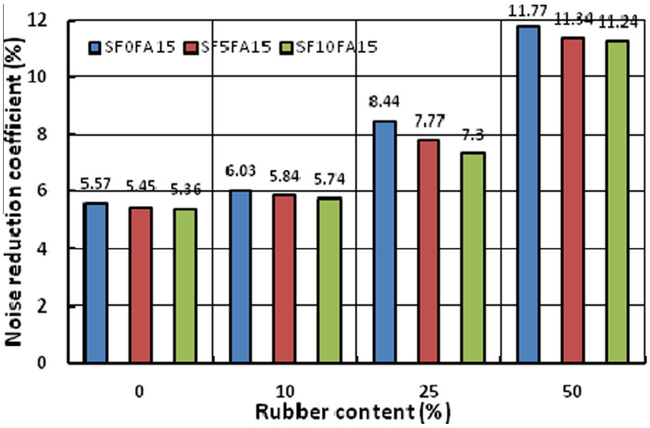

Figure 24. Effect of rubber sand content on the sound reduction coefficient of concretes (Mohammed et al., 2012).

From the above mentioned studies in this section, it can be concluded that the inclusion of rubber sand in the matrix increased its energy absorption. The improvement of the energy absorption with the inclusion of rubber sand is one advantage of using this recycled material.

17. Sound absorption

Sukontasukkul (2009) partially replaced natural sand in concretes with two different particle sizes of crumb rubber at levels of 0%, 10%, 20% and 30%, by volume. The sizes of crumb rubber were No. 6 (passing sieve No. 6) and No. 26 (passing sieve No. 26). Results showed an increase in the noise reduction coefficient with the inclusion of rubber sand. The increment in the noise reduction coefficient was 40%, 40.57% and 22.72% with the inclusion of 10%, 20% and 30% rubber sand with large size, respectively, whilst it was approximately 41%, 25.58% and 46.37%, respectively, with the inclusion of small size rubber sand (Khaloo et al., 2008) replaced natural sand in concretes with rubber (maximum size 4.75 mm) at levels of 25%, 59%, 75% and 100%, by volume. They reported that the sound absorption by concrete increased with increasing rubber sand content, of which the velocity of ultrasonic waves reduced significantly with increasing rubber sand content. Mohammed et al. (2012) reported better sound absorption of concretes containing rubber (size 0.6 mm) as natural sand replacement compared to the conventional concrete. The noise reduction coefficient increased as the rubber sand content increased (Fig. 24). Najim and Hall (2012) reported that SCCs containing crumb rubber (size 6–2 mm) as natural sand replacement at levels of 5%, 10% and 15%, by weight, exhibited superior vibration damping behaviour compared to the control. Bowland et al. (2012) reported that ground rubber (maximum size of 0.25 mm) mixed with latex which replaced natural sand at levels of 5%, 10% and 15%, by volume, in concrete mixtures improved damping characteristics. Eiras et al. (2014) reported an increase in the damping properties of mortars

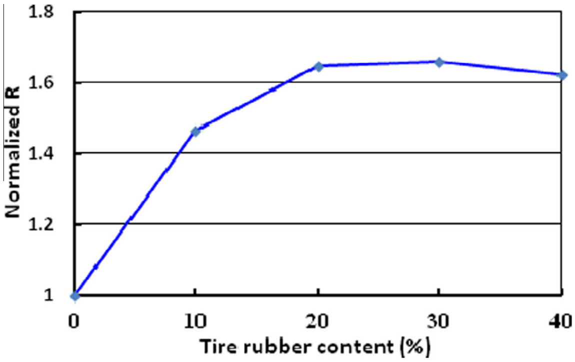

Figure 25. Normalised cracking resistance (R) of ECC mixtures (Huang et al., 2013).

by partially replacing natural sand with crumb rubber (size ∼0.08–1.3 mm) at levels of 40%, 50% and 60%, by volume. The damping properties increased with increasing rubber sand content. Gisbert et al. (2014) reported that mortars containing crumb rubber as natural sand replacement at levels of 10%, 20%, 30% and 40%, by weight, exhibited superior damping behaviour compared to the control. The damping increased with increasing the rubber sand content. They also reported that if the percentage of crumb rubber is higher, the presence of rubber can cause sound absorption if a finer granulometry is involved (size 0.25 mm).

From the above discussion in this section, it is safe to conclude that the inclusion of rubber sand in the matrix increased its sound insulation. The increment in the noise reduction coefficient of the matrix with the inclusion of rubber sand is one advantage of using this waste material. Because of this advantage, rubberised concrete can be used as sound barriers. The rubber sand in this case cannot be considered as waste material, but can be considered as valuable material.

18. Electrical resistance

Yung et al. (2013) reported higher electrical resistance of rubberised concrete in comparison with the plain concrete. The electrical resistance increased as the rubber sand content increased. The inclusion of rubber (size 0.6 mm) increased the surface resistance by 17%. Mohammed et al. (2012) reported an increase in the electrical resistivity of hollow concrete blocks manufactured by partially replacing natural sand with crumb rubber (size 0.6 mm) at levels of 10%, 25% and 50%, by volume, compared to the control. The electrical resistance increased with increasing rubber sand content.

From the above mentioned studies in this section, it can be clearly noted that there is a distinct lack of studying the effect of rubber sand on the electrical resistance of mortar/concrete. The electrical resistance of mortar/concrete containing rubber sand still needs more investigations. According to the available earlier studies, it can be concluded that the electrical resistance increased with the inclusion of rubber sand.

19. Cracking resistance

Jingfu and Yongqi (2008) reported that the inclusion of 20% rubber (average size 1.5 mm), by volume, as natural sand replacement retarded the cracking time about 24 h in comparison with the plain mortar. Huang et al. (2013) studied the cracking resistance of ECC mixtures containing tyre rubber as partially replacement of iron ore tailings that were used as aggregate at levels of 0%, 10%, 20%, 30% and 40%, by volume. Results showed that the ECC containing rubber sand exhibited higher cracking resistance than the control (Fig. 25), implying that the inclusion of rubber sand led to lower cracking tendency under restrained drying shrinkage. They also concluded that higher tyre rubber aggregate content led to reduce the crack width, crack length and crack number in the matrix. Ganesan et al. (2013) partially replaced natural sand in concrete of beam-column joints with rubber (maximum size 4.75 mm) at levels of 0% and 15%, by volume. They reported that the addition of shredded rubber could bring about improvement in the beam-column joint behaviour under cyclic loads in terms of crack resistance. Nguyen et al. (2012) partially replaced natural sand in mortars containing 40 kg/m^3 fibres with rubber (size 1.4–0.65 mm) at levels of 0%, 20% and 30%, by volume. Results showed a reduction in the width of shrinkage cracks with the inclusion of rubber sand. The shrinkage cracks width was reduced by 30.23% and 51.2% with the inclusion of 20% and 30% rubber sand, whilst the increment in crack time was 20% and 60%, respectively. Khaloo et al. (2008) replaced natural sand in concretes with crumb rubber (maximum size 4.75 mm) at levels of 0%, 25%, 50%, 75% and 100%, by volume. They reported that cracking width in rubberised concretes was smaller than that of the plain concrete and the propagation of failure symptoms was more gradual and uniform.

20. Usability of rubberised mortar/concrete

In general view, using rubber as fine aggregate in mortar and concrete showed some advantages, of which some properties are improved, and some disadvantages, of which some properties are defected. The advantages of using rubber sand are decreasing density, improving impact energy, improving impact load, increasing toughness, increasing ductility, increasing freeze/thaw resistance, increasing thermal insulation, increasing sound insulation, increasing damping capacity, increasing strain capacity, reducing micro-cracks after firing, increasing abrasion resistance (according to rubber sand content and w/c ratio) increasing resistance against HCl attack, improving energy absorption, increasing electrical resistance and increasing cracking resistance. On the other hand, the disadvantages of using rubber sand are decreasing workability, increasing bleeding, decreasing mechanical strength, increasing drying shrinkage, decreasing carbonation resistance, decreasing corrosion resistance (rubber sand content $\geqslant$ 10%), increasing water absorption, increasing chloride ion penetration depth and decreasing sulfuric acid resistance.

It is safe to conclude that rubber sand can be used for manufacturing lightweight concrete; non-structural works; decreasing the risk of spalling caused by exposure to elevated temperatures; as safety barriers with improved resistance to traffic noise, as sound barriers, as a sound absorber; in highway construction as a shock absorber; in buildings as an earthquake shock-wave absorber (Topcu and Avcular, 1997); as construction material where thermal insulation, sound insulation, and acoustic anti-vibration properties are required; and as construction material where high resistance for impact load is required (rail foundations, tram-rail beds). Furthermore, rubberised concrete can be used in foundation pads for machinery and in the railway station where vibration damping is required; in railway buffers, jersey barriers, bridge abutment fill and bunkers where resistance to impact or explosion is required,for pipe bedding and trench filling, in artificial roof construction, for pile heads and as paving slabs.

21. Remarks

The current review paper aims to review the previous works that were carried out on the fresh properties, mechanical properties, impact energy, impact load, toughness, ductility, shrinkage, abrasion resistance, freeze/thaw resistance, carbonation resistance, corrosion resistance, water absorption, porosity, chloride ion penetration, resistance to aggressive environmental, thermal insulation, energy absorption, sound absorption, electrical resistance and cracking resistance of mortar/concrete based on PC containing rubber as fine aggregate replacement. The remarks of this literature review can be summarized as follows:

1. Most of the previous studies believed that the inclusion of rubber sand in the mixture reduced workability. On the other hand, a few other studies believed the positive effect of rubber sand on workability. The inclusion of rubber sand in the mixture increased bleeding and setting time.
2. The inclusion of rubber sand in the mixture reduced fresh and dry density. This reduction increased with increasing rubber sand content.
3. The inclusion of rubber sand in the mixture reduced the mechanical strength. This reduction increased with increasing rubber sand content. This can be mitigated by replacing a suitable part of cement with SF or treating rubber particles with NaOH aqueous solution or in water-soaking. Also, mixing rubber particles with latex before they are added to the matrix was recommended to improve the strength.
4. The inclusion of rubber sand in the mixture, up to 50%, improved impact energy. Rubber sand, up to 20% improved impact load behaviour.
5. Most of the previous studies believed higher toughness with the inclusion of rubber sand. The inclusion of rubber sand in the mixture increased its ductility and strain capacity.
6. The inclusion of rubber sand in the matrix increased its shrinkage. The shrinkage increased with increasing rubber sand content.
7. Rubber sand increased the abrasion resistance of concrete if appropriate rubber sand content and suitable w/c ratio were used. The inclusion of 5% rubber sand in concrete led to anti-sulphate corrosion resistance. More than 10% rubber sand in concrete increased the reinforcing bar mass loss. Rubber sand increased the resistance of freeze/thaw of the concrete. The freeze/thaw resistance increased with increasing rubber sand content.
8. In general, the inclusion of rubber sand in the mixture increased its percentage of water absorption and porosity, but it is mainly dependent on the rubber particle size and rubber sand content.
9. Rubber sand increased the chloride ion penetration. This can be mitigated by replacing 10% of cement with SF or replacing part of cement with FA.
10. Rubber sand reduced the carbonation resistance of concrete. The reduction in the carbonation resistance slightly increased with increasing rubber sand content.
11. The inclusion of rubber sand in the mixture increased its resistance against HCl. On the other hand, the inclusion of rubber sand led to a higher mass loss degree after exposure to sulphuric acid. This reduction increased with increasing rubber sand content.
12. The inclusion of rubber sand in the mixture increased its thermal insulation, sound absorption, energy absorption and electrical resistance. These properties increased with increasing rubber sand content. On the other hand, the inclusion of rubber sand in the mixture reduced its fire resistance.
13. The inclusion of rubber sand in the matrix exhibited higher cracking resistance and retarded the cracking time.

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