Construction and Building Materials 229 (2019) 116901

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Novel approach to improve crumb rubber concrete strength using thermal treatment

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HIGHLIGHTS

- A novel approach for treating crumb rubber before incorporation into the concrete.
- Thermally-treated rubber has a relatively strong bond with the concrete matrix.
- The effects of heating time, rubber size, and rubber content have been investigated.
- Significant increase in compressive and tensile strengths of crumb rubber concrete.

ARTICLE INFO

Article history:
Received 4 May 2019
Received in revised form 3 August 2019
Accepted 5 September 2019
Available online 14 September 2019

Keywords:
Rubberised concrete
Crumb rubber
Thermal-treatment
Compressive strength
Tensile strength

ABSTRACT

The concept of using crumb rubber as a partial replacement of natural aggregate in concrete to produce rubberised concrete and reduce environmental impacts has been a subject of research for many years. A plethora of studies have investigated various methods to improve the rubberised concrete strength using different pre-treatment methods for the rubber particles and/or using other additives for general concrete strength enhancement. However, the efficiency and applicability of these methods have been quite inconsistent and in some cases in conflict with each other. This study presents a novel approach to pre-treating crumb rubber particles using thermal treatment at 200 °C before incorporation into concrete. Heating time, rubber size, and rubber content were the variables in this experimental investigation. Scanning electron microscope (SEM) investigation was carried out on both as-received and thermally-treated rubber particles, as well as crumb rubber concrete (CRC) specimens. The results showed promising enhancements in concrete performance compared with the previous work findings. At 20% rubber content using size #40 mesh thermally-treated rubber, the compressive strength recovered by 60.3%.

1. Introduction

The amount of used tyres being sent to landfill is a significant environmental problem. Worldwide, more than 1.0 billion tyres are produced and are expected to be discarded to landfill every year [1]. In Australia, 49 million tyres are disposed of annually and only 16% of those are recycled [2]. Tyres are unable to be buried in landfill due to their properties such as low density and poor degradation ability. The accumulation of used tyres in landfill poses environmental issues such as fuel for fires which cause uncontrolled pollution, providing a breeding ground for mosquitoes, and producing a mix of chemicals that can harm the environment and contaminate the soil and vegetation [3]. Since rubber tyres are a non-biodegradable material, their proposed use in concrete as a partial aggregate replacement addresses and aids in combating these environmental issues, and can potentially extend their lifespan by an additional 100 years.

The strength of crumb rubber concrete (CRC) is low compared with that of traditional concrete, due to the hydrophobic nature and low stiffness of rubber. While the concrete is curing, rubber repels water, which disturbs the flow of water in the concrete matrix and hence leads to lower curing efficiency. In addition,

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https://doi.org/10.1016/j.conbuildmat.2019.116901
0950-0618/

the low stiffness of rubber helps it stretch or compress under stress resulting in crack propagation in the surrounding cement paste [4]. This leads to the imperfection of bond at the rubber/cement interface, hence leading to strength reduction [5]. Most researchers have reported that crumb rubber aggregate results in lower strength losses compared to those when using coarse rubber aggregate [6–10]. This is ascribed to the fact that the crumb rubber particles cause less voids in concrete and they have relatively better adhesion with the surrounding cement material.

Rubber products are a combination of long polymer chains which are mostly crosslinked with sulphur bridges, giving a complex structure. Recovery and recycling of rubber products presents challenges owing to the irreversible sulphur bonds between rubber chains [11]. Many studies have suggested modifying the surface of rubber particles through physical or chemical treatment to change their hydrophobicity and consequently increase their bonding with cement in order to improve the compressive strength of CRC [12–17]. Li et al. [18] reviewed the performance of high-strength CRC. They concluded that when using as-received rubber in conjunction with less than 10% rubber content by volume, the strength losses were about 25%. If the rubber content is no more than 20%, the strength losses were about 30%. When rubber content was higher than 20%, the strength significantly decreases. Several approaches have been established and developed to improve the strength of CRC. These approaches are mainly directed to enhance the rubber particle's surface by water washing, chemical treatments or coating rubber particles with different materials, to enhance the bond between the rubber particles and the cement matrix. However, the experimental findings of these approaches are quite inconsistent and in some cases conflict with each other. At 20% rubber content, Mohammadi et al. in [12] and in [16] reported 28% and 11.2% strength recoveries when treating rubber for 24 h by Sodium Hydroxide (NaOH) solution and soaking in water, respectively. However, at the same rubber content, Youssf et al. [17] showed that NaOH rubber treatment for more than 0.5 h (strength recovery of 35.2% at 0.5 h) adversely affected the strength. In addition, Youssf et al. in [19] showed only 22.3% strength recovery when soaking rubber in water for 24 h. The strength recovery is the ratio between the strength gained (by pre-treating rubber) to the strength lost when using as-received rubber, see Eq. (1). Najim and Hall [15] washed rubber with water and showed 6.8% strength recovery when applied on 38% rubber content.

Huang et al. [20] suggested an approach for enhancing the performance of rubber-modified cement composites through two stages. They modified the rubber particle surface by using silane coupling agent, then cement was used to coat the treated rubber particle. Later, this approach has been improved by Dong et al. [13] by developing a cementitious coating layer around rubber particles with silane coupling agent. They observed 21% and 36.7% compressive strength recovery at 15% and 30% rubber content, respectively. Onuaguluchi [14] coated rubber (15% rubber content) particles with limestone powder, and recorded 15% strength recovery. Balaha et al. [21] applied NaOH solution pre-treatment for mixtures included 20% rubber content and were able to decrease the strength losses by 10%. Other researchers also reported CRC strength enhancements through a range of pre-treatment methods including: Eldin and Senouci [22]; Pelisser et al [23]; Su et al. [24]; and Hamza and Ghedan [25].

$$Strength\ recovery(\%) = \frac{\boldsymbol{S_{TR}} - \boldsymbol{S_{AR}}}{\boldsymbol{S_C} - \boldsymbol{S_{AR}}} \tag{1}$$

where S_{TR}, S_{AR}, and S_C are the strengths of treated rubber concrete, as-received rubber concrete, and control concrete, respectively.

Other researchers who reported negligible improvement in compressive strength, even though they used pre-treatments that were basically the same as those reported in the previous paragraphs included: Deshpande et al. [26]; Tian et al. [27]; Li et al. [28]; Turatsinze et al. [29]; Albano et al. [30], and Raffoul et al. [31]. For example, Tian et al. [27] observed that rubber pre-treatment with the inorganic salt Calcium Chloride ($CaCl_2$) improved the strength of CRC; however, organic, acidic, and alkaline solutions did not effectively enhance CRC strength. Raffoul et al. [31] tried pre-wash of rubber by water and then air drying, without getting any strength improvement.

Despite the findings of all these studies, applying chemical modification in the course of preparing concrete is probably not favourable to the construction industry due to the chemical waste that is generated, the higher costs that are added, and the longer processing time. Due to the compressive strength losses and the issues with the rubber pre-treatment methods tried to date, CRC use in structural applications in the construction industry is still limited, primarily to laboratory tests [32–40]. This paper introduces a new and novel approach of rubber pre-treatment by conducting thermal curing of the rubber particles before mixing them into concrete. The hypothesis in this research is that thermal treatment would change the rubber particle's surface topology, as well as its stiffness, which would improve the strength of CRC. The morphology of crumb rubber particles after thermal treatment was studied and compared to that of as-received rubber. The mechanical properties including compressive and tensile strengths were measured to test the CRC performance using the proposed pre-treatment approach. The results of this study may open a new route of pre-treating crumb rubber that may be attractive to a wide range of applications in the construction industry.

2. Experimental program

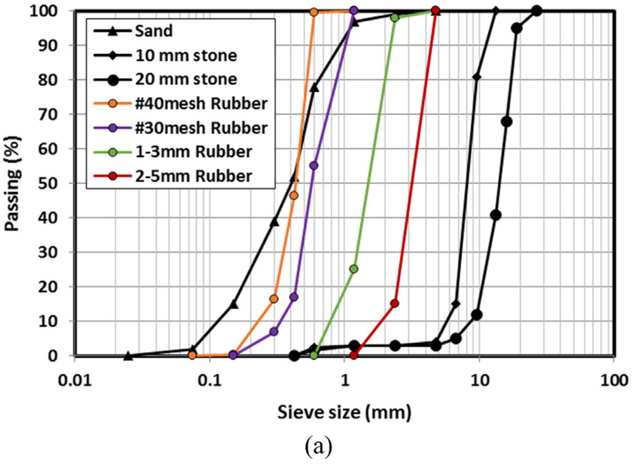
2.1. Materials

General purpose cement of 3.15 specific gravity, according to the Australian Standard (AS) 3972-2010 [41], was used as the binder for all concrete mixtures. Two nominal sizes of dolomite stone as coarse aggregates, 10 and 20 mm, with specific gravity of 2.72, unit weight of 1590 kg/m^3 were added. Natural river sand with a maximum aggregate size of 5 mm, specific gravity of 2.65 and unit weight of 1420 kg/m^3 was employed as fine aggregate. Four different sizes of commercial crumb tyre rubber were added separately to the mixtures with product names; #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm. The specific gravity and unit weight of rubber used was 1.15 ± 0.012 and 530 kg/m^3, respectively. Fig. 1(a) provides the sieve analysis of each concrete aggregate used. Fig. 1(b) shows the sieve analysis of the overall mixed fine aggregates (sand and different rubber sizes) with the standard grading limits according to AS 2758.1:2014 [42]. Superplasticizer (MasterGlenium SKY 8708) with specific gravity of 1.085 was added to control the concrete workability.

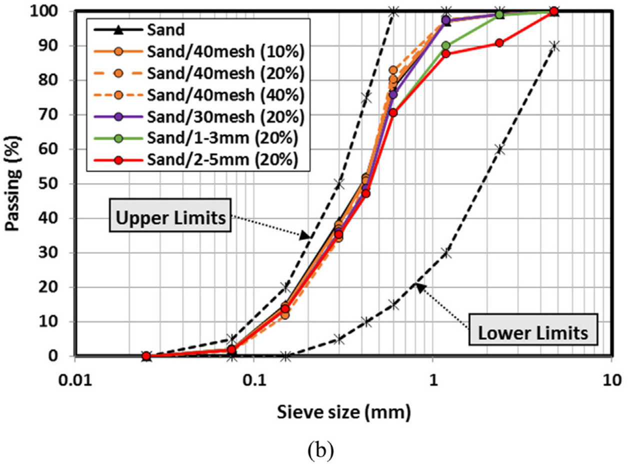
2.2. Preparation and concrete casting

Preparation procedures followed in this study were as per the AS 1012.2:1994 [43]. Non-treated rubber (as-received) and thermally-treated rubber were used in the course of this study. The thermally treated crumb rubber was prepared using a common furnace at constant temperature of 200 °C. It is noteworthy that the furnace was connected to a duct and funnel filter which sucks and filters all smoke before transferring into the air for more environmental safety. Three different heating times were used namely; 1 h, 1.5 h, and 2 h. Each 150 g of as-received crumb rubber was placed into an aluminium foil tray of 250 × 300 mm and then transferred to the preheated furnace. The thermally treated rubber was then moved into a fume hood to cool down and be weighed. The specific gravity of the thermally-treated rubber was measured as 1.19 ± 0.015. It was also noticed that some of the rubber particles were clumped together into larger pieces after the thermal treatment. These pieces were simply broken up back into finer particles by smashing them with a mallet. Fig. 2 shows the method of preparing thermally treated rubber. Crumb rubber was used at fractions of 0, 10, 20, and 40% by volume as a partial replacement of the concrete fine aggregate. At 20% rubber content, different rubber sizes of #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm were used to investigate the effect of rubber particle size on the proposed treatment approach. Table 1 summarises the different components of all concrete mixtures used in this study.

The concrete mixtures were designed according to AS 1012.2 [44]. The target compressive strength of the control mix (M1) was 50 MPa. All mixtures were designed with constant water to cement (W/C) ratio of 0.5 and SP dosage of 0.55% by cement weight. The fine/coarse aggregate ratio was 1/1.2 by weight. The



(a)



(b)

Fig. 1. Sieve analysis of: (a) each concrete aggregate used, and (b) overall mixed fine aggregates.

10 mm /20 mm coarse aggregate ratio was 1/2.34 by weight. The mixing procedure for both conventional concrete and CRC mixtures was as follows: mix dry sand and stone for 1 min.; add half of the water and mix for 1 min.; rest for 2 mins.; add cement, water, and admixtures, and then mix for 2 mins. Nine standard 100 × 200 mm cylinders were prepared from each mixture for measuring the compressive strength and splitting tensile strength. The cast concrete was compacted by using a standard compaction rod and hammer. The specimens were demoulded after 24 h and labelled for the various tests. Then they were cured in a water bath at 23 ± 2 °C according to AS1012.8.1[45].

2.3. Testing characterizations

A scanning electron microscope (JSM-7800F) at 10 kV was employed to study the morphology of the crumb rubber particles before and after thermal treatment. In addition, it was reused to scan the bond connections between rubber particles and the surrounding concrete matrix for tested CRC specimens. The uniaxial compressive strength test, according to AS 1012.9 [46], and splitting tensile strength test, according to AS 1012.10 [47], were selected to examine the CRC performance at concrete ages of 7 and 28 days. The compressive load was applied at a constant rate of 2.6 ± 0.25 kN/s, and the splitting tensile test load was applied at a constant rate of 0.8 ± 0.02 kN/s. Each test was carried out on three specimens and average results were analysed and compared.

3. Results and discussion

3.1. Morphology of crumb rubber particles

It is imperative to investigate the effect of thermal treatment on crumb rubber particles at the micro-scale to elaborate the mechanism of this treatment on each rubber category and how it influences the concrete performance. Crumb rubber size #40 mesh has been chosen for this investigation. Fig. 3 presents scanning electron microscope (SEM) images of as-received and thermally-treated crumb rubber. At low magnification of 100μ, Fig. 3(a) shows that the as-received crumb rubber consists of two constituents; rubber particles (pointed at by red arrows) and impurities (pointed at by yellow arrows) that are attached or close to the rubber particles. At higher magnifications of 10 μm, Fig. 3(b) shows how those impurities stick to the rubber particle surface. These masses are expected to be found in the as-received crumb rubber because of its source which is from recycled car tyres that consist of crumb rubber, cords, steel, and fibres [48,49]. Although processing the crumb rubber includes removing all constituents but rubber, it still has remnants from those impurities within the rubber particles. Those impurities develop an immediate barrier against good contact with surrounding concrete materials. Consequently, it adversely affects the crack bridging effect of rubber in rubberised concrete [5,50–52]. Fig. 3(c, d, and e) show the influence of the thermal treatment on the crumb rubber particles. At the low magnification, it can be seen that most of the unwanted impurities have disappeared leaving a high content of rubber particles. Fig. 3(e) indicates the enhancement in crumb rubber particles after heating. Crumb rubber particles become relatively clean and could have higher mechanical interlocking ability to the other concrete constituents, which can contribute to improving the CRC performance.

3.2. Morphology of CRC

The bond efficiency at the interfacial transition zone between the rubber particles and surrounding cementitious materials in concrete was scanned at a micro-scale to elaborate the influence of the proposed thermal treatment on the concrete performance. The samples used for this investigation were taken from tested concrete cylinders under compression [19]. Fig. 4 shows SEM

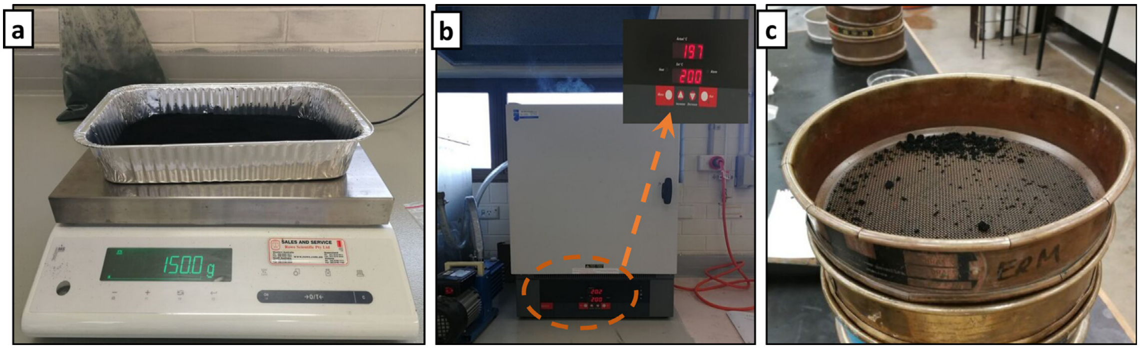


Fig. 2. Method followed to prepare the thermally-treated rubber: (a) 150 g of as-received crumb rubber in aluminium foil tray; (b) common furnace used; and (c) clumped rubber particles.

Table 1
Proportions of concrete mixtures.

Mixture no.	Mixture code	Rubber content (%)	Rubber size	Rubber heating time (hr)	Mixture proportions (kg/m^3)						
					Cement	Water	Sand	Rubber	Stone 10 mm	Stone 20 mm	SP
M1	Control	0	–	–	351	176	869	0.0	312	730	1.94
M2	AR10-#40	10	#40 mesh	–	351	176	783	37.7	312	730	1.94
M3	AR20-#40	20	#40 mesh	–	351	176	696	75.5	312	730	1.94
M4	AR40-#40	40	#40 mesh	–	351	176	522	151.0	312	730	1.94
M5	AR20-#30	20	#30 mesh	–	351	176	696	75.5	312	730	1.94
M6	AR20-S1-3	20	1–3 mm	–	351	176	696	75.5	312	730	1.94
M7	AR20-S2-5	20	2–5 mm	–	351	176	696	75.5	312	730	1.94
M8	TT10-#40	10	#40 mesh	1.0	351	176	783	39.1	312	730	1.94
M9	TT20-#40	20	#40 mesh	1.0	351	176	696	78.1	312	730	1.94
M10	TT40-#40	40	#40 mesh	1.0	351	176	522	156.2	312	730	1.94
M11	TT20-#30	20	#30 mesh	1.0	351	176	696	78.1	312	730	1.94
M12	TT20-S1-3	20	1–3 mm	1.0	351	176	696	78.1	312	730	1.94
M13	TT20-S2-5	20	2–5 mm	1.0	351	176	696	78.1	312	730	1.94
M14	TT20-S2-5	20	2–5 mm	1.5	351	176	696	78.1	312	730	1.94
M15	TT20-S2-5	20	2–5 mm	2.0	351	176	696	78.1	312	730	1.94

AR *= Rubberised concrete with as-received rubber.*
TT *= Rubberised concrete with "thermally treated" rubber.*
SP *= Superplasticizer.*

images of CRC with as-received rubber and thermally-treated rubber at two different rubber sizes, namely CRC with rubber size #40 mesh (0.42 mm) and CRC with rubber size 2–5 mm.

The interfacial bond between the concrete matrix and crumbed rubber is identified by the red oval over the SEM images (a–d). Fig. 4(b and d) shows that thermally-treated rubber particles still have relatively strong bond with the concrete matrix even after destructive compression tests, while Fig. 4(a and c) show a clear weakness in the bond between as-received crumb rubber and the concrete matrix. These promising strong bonds when using thermally-treated crumb rubber have been confirmed by the mechanical tests described in Section 3.3.

By comparing the results in Fig. 4(b and d), the small rubber size (#40 mesh) has a higher bond compared with the large rubber size (2–5 mm). This observation has been confirmed by the mechanical tests in which CRC with fine crumb rubber particles achieved higher compressive and tensile strengths than those of CRC with coarser crumb rubber particles after thermal treatment.

The hypothesis made herein is that thermal treatment could address the limitation of using crumb rubber in concrete by changing the topology and mechanical characteristics of the rubber particles' surface and their stiffness, which consequently favours the strength of rubberised concrete. As-received crumb rubber contains a high content of rubber particles but also impurities of other materials such as fibres and cords as seen in SEM images, Fig. 3(a and b). These impurities fold around and stick to rubber particles, thus forming a barrier layer between the rubber particles and surrounding concrete. Moreover, these impurities create weak points for crack initiation under stresses. Upon loading, the load transfer between concrete and rubber does not happen efficiently and the cracks occur at the weakest point of the rubber/concrete interface. Thermally-treated rubber has less impurities with considerable clean surface as shown in SEM images, Fig. 3(c, d and e). Heating crumb rubber improves two main things: (i) it burns out most of the impurities and fibres attached to the rubber particle's surface; and (ii) it improves the mechanical properties of the rubber particles' surface. The first improvement helps the rubber particles to strengthen the bond and interlock with concrete. The second improvement is elaborated as the thermal treatment creating an outer hard shell on the rubber particle, lessening its softness at the interface. This reduces the volume of softness within the concrete matrix and hence, the load can transfer with relatively higher efficiency between rubber particles and concrete, resulting in promoting CRC compressive and tensile strength. Fig. 5 shows a schematic drawing representing the interface between rubber and surrounding concrete for both as-received and thermally-treated crumb rubber.

3.3. Mechanical properties

In this section, the effects of rubber thermal pre-treatment at different rubber contents, rubber sizes, and heating times on CRC compressive strength (at 7 and 28 days) and indirect tensile strength (at 28 days) are discussed. Table 2 shows the recorded properties for each mixture.

3.3.1. At different rubber contents

The effects of rubber thermal pre-treatment at different rubber contents on concrete compressive and indirect tensile strengths were determined through comparison of the results of mixtures M1-M4 and M8-10. This was measured at constant rubber size of #40 mesh and heating time of 1 h, then plotted in Fig. 6. As shown in the figure, using as-received rubber content of 10%, 20%, and 40% decreased the compressive strength by 22%, 46%, and 73%, respectively at 7 days, and by similar values of 21%, 40%, and 73%, respectively at 28 days. These incremental strength losses are similar to those reported in the literature [16,53,54]. However, thermally-treated rubber recorded impressive results. Using thermally-treated rubber content of 10%, 20%, and 40% decreased the compressive strength by only 11%, 19%, and 37%, respectively at 7 days, and by only 1.6%, 16%, and 38%, respectively at 28 days. The thermal treatment for rubber recovered 49%, 58%, and 49% of the compressive strength losses at 7 days, and recovered 93%, 60%, and 47% at 28 days, respectively when using 10%, 20%, and 40% rubber contents. This was attributed to the relatively improved contact at the rubber/cement interfacial transition zone showed obviously in Fig. 4. This also indicated the effectiveness of this rubber pre-treatment approach, especially at high rubber content, which attributed to the increased rubber stiffness with heating, and hence less adverse effects compared to those of as-received rubber.

Fig. 6(c) shows the effect of rubber content on the 28 day indirect tensile strength. Similar to its effect on the compressive strength, the as-received rubber showed continuous increase in tensile strength losses with rubber content increase. However, remarkable tensile properties results were observed in the case of using thermally treated rubber. The thermal treatment for

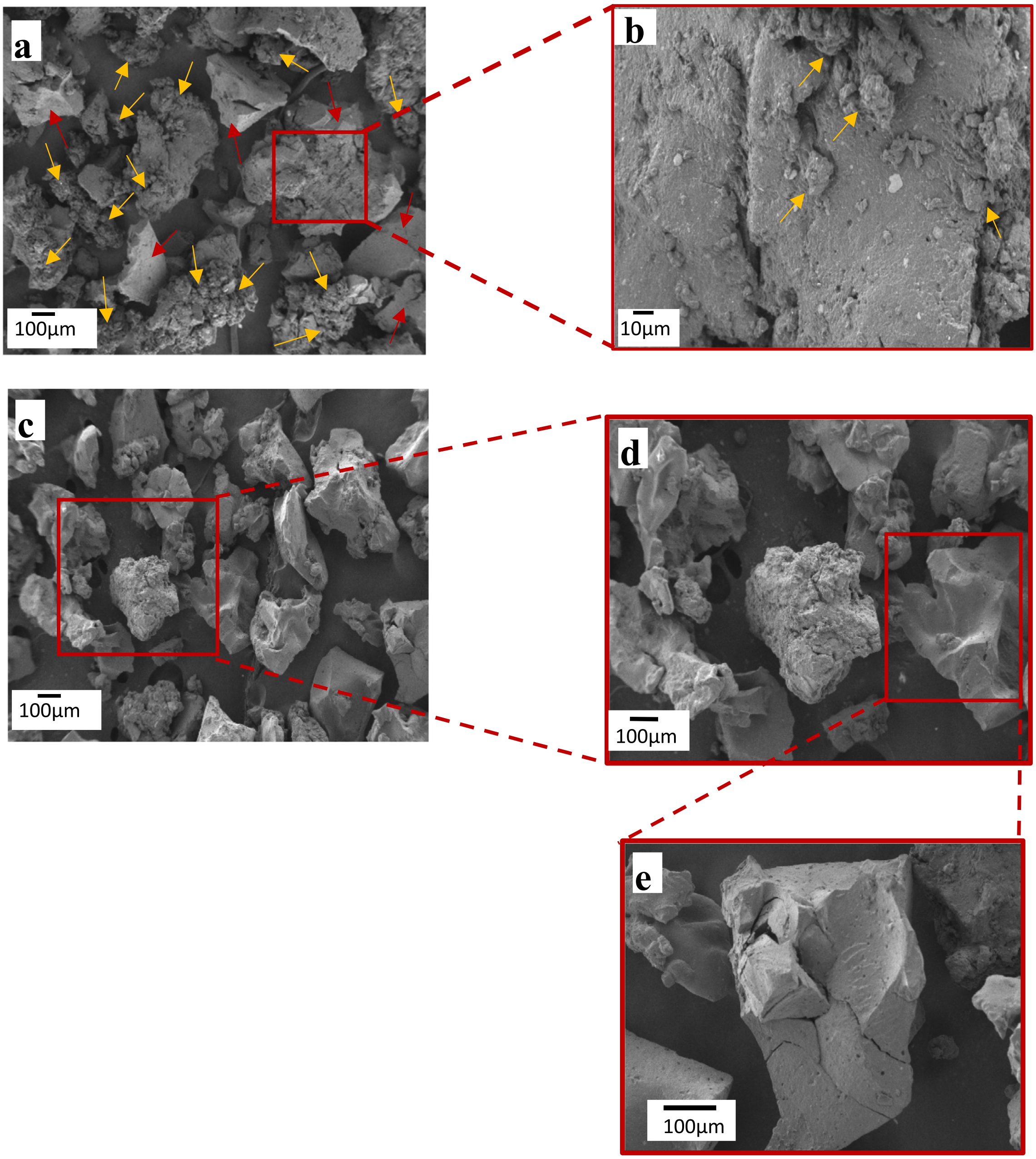


Fig. 3. SEM images of crumb rubber particles: (a and b) as-received, and (c, d, and e) thermally-treated.

rubber recovered 106%, 82%, and 57%, respectively when using 10%, 20%, and 40% rubber contents. This indicated even better positive influence of using this thermally-treated rubber on CRC tensile performance than that showed in the corresponding compressive performance.

Aslani [55] explored the effect of rubber content on mechanical properties of CRC using an extensive databases of previous studies. Their results showed that, the losses in tensile strength are always less than the loss compressive strength. Kaloush [56] added that, with increasing the rubber content, the tensile strength decreased but the strain at failure increased which means more ductility. These reasons explain why tensile strength achieved a higher enhancement than the compressive strength even with a positive influence at 10% TT rubber contents.

Furthermore, the results in Fig. 6 confirm the inverse relationship between CRC's compressive strength and rubber content in the concrete mixture. Increasing the as-received rubber content in concrete mixture leads to a decrease in the compressive strength. This inverse relationship become slower in the case of thermally-treated rubber. For example, the difference in compressive strength between TT and AR with 40% rubber content at 28 days is much higher than the difference in compressive strength between TT and AR with 10% rubber content at 28 days, equal to 31.3 MPa and 10.1 MPa, respectively. This relates to the improvement in the stiffness of rubber particles after thermal treatment. In other words, with increasing the as-received rubber content, the strength of concrete decreases because of the increased number of weak positions in the concrete mixture. However, by

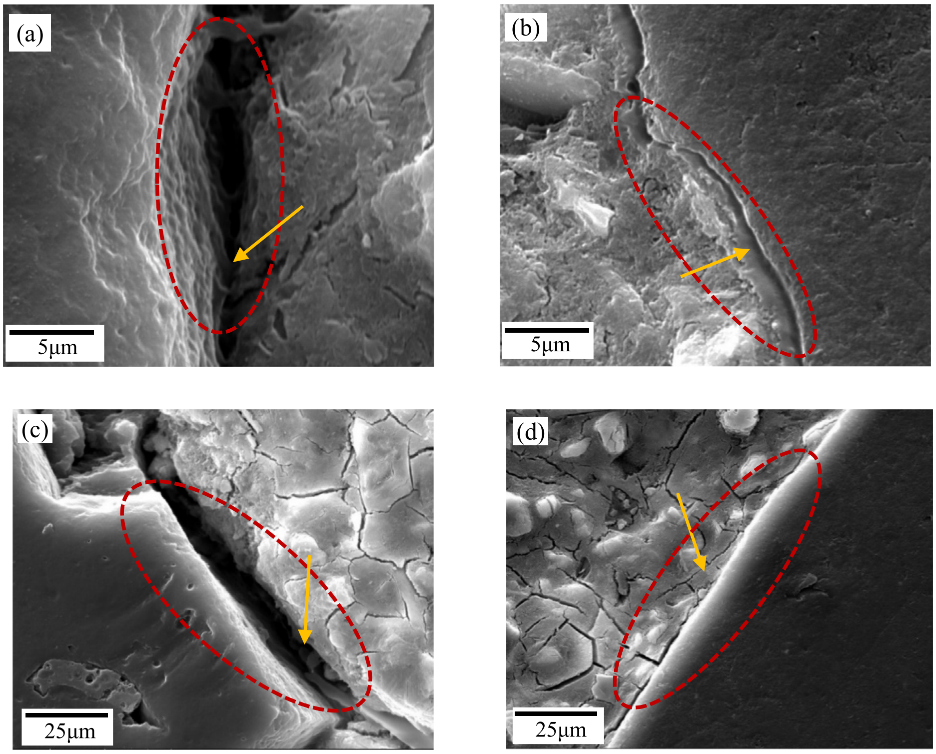


Fig. 4. SEM images of the bond between the concrete matrix and rubber particles for: (a) as-received size #40 mesh, (b) thermally-treated size #40 mesh, (c) as-received size 2–5 mm, and (d) thermally-treated size 2–5 mm.

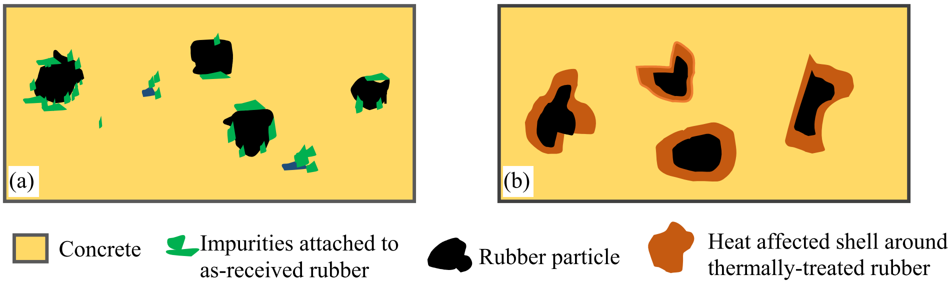
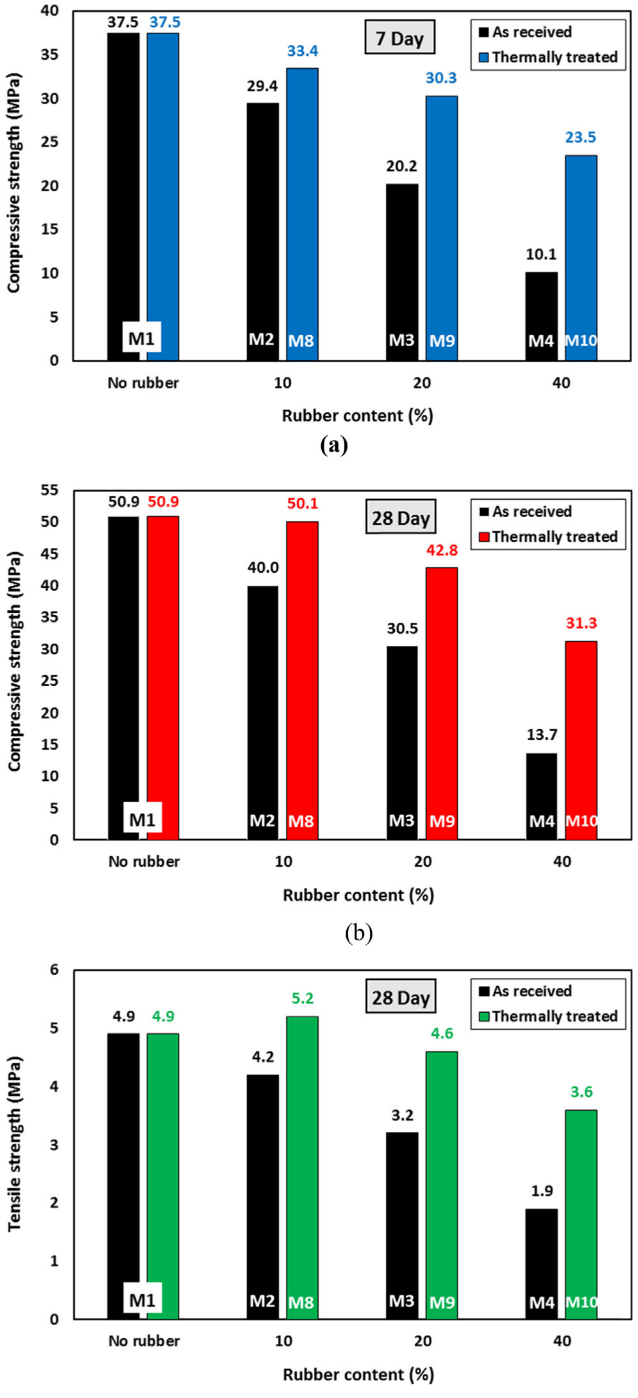


Fig. 5. Schematic illustration of the rubber/concrete interface: (a) CRC with as-received rubber and (b) CRC with thermally-treated rubber.

Table 2
Measured mechanical properties of concrete mixtures.

Mixture no.	Mixture code	Rubber content (%)	Rubber size	Rubber heating time (hr)	Compressive strength (MPa)		Indirect tensile strength (MPa)
					7 day	28 day	28 day
M1	Control	0	–	–	37.5 ± 0.12	50.9 ± 1.65	4.9 ± 0.09
M2	AR10-#40	10	#40 mesh	–	29.4 ± 0.40	40.0 ± 0.24	4.2 ± 0.10
M3	AR20-#40	20	#40 mesh	–	20.2 ± 2.50	30.5 ± 0.69	3.2 ± 0.15
M4	AR40-#40	40	#40 mesh	–	10.1 ± 1.00	13.7 ± 1.41	1.9 ± 0.01
M5	AR20-#30	20	#30 mesh	–	23.5 ± 0.05	32.5 ± 0.18	3.2 ± 0.10
M6	AR20-S1-3	20	1–3 mm	–	24.0 ± 0.65	33.3 ± 0.11	3.6 ± 0.10
M7	AR20-S2-5	20	2–5 mm	–	24.4 ± 0.96	33.6 ± 0.61	3.8 ± 0.06
M8	TT10-#40	10	#40 mesh	1.0	33.4 ± 2.30	50.1 ± 0.03	5.2 ± 0.30
M9	TT20-#40	20	#40 mesh	1.0	30.3 ± 0.36	42.8 ± 0.48	4.6 ± 0.23
M10	TT40-#40	40	#40 mesh	1.0	23.5 ± 0.40	31.3 ± 0.97	3.6 ± 0.10
M11	TT20-#30	20	#30 mesh	1.0	29.5 ± 0.44	41.6 ± 2.31	4.5 ± 0.08
M12	TT20-S1-3	20	1–3 mm	1.0	26.3 ± 0.66	39.2 ± 0.89	4.2 ± 0.02
M13	TT20-S2-5	20	2–5 mm	1.0	24.8 ± 0.15	34.6 ± 1.80	4.0 ± 0.23
M14	TT20-S2-5	20	2–5 mm	1.5	26.0 ± 0.27	36.9 ± 0.71	4.5 ± 0.17
M15	TT20-S2-5	20	2–5 mm	2.0	26.1 ± 0.08	37.2 ± 0.70	4.1 ± 0.11

***AR* =** *Rubberised concrete with as-received rubber.*
***TT* =** *Rubberised concrete with "thermally treated" rubber.*
***SP* =** *Superplasticizer.*

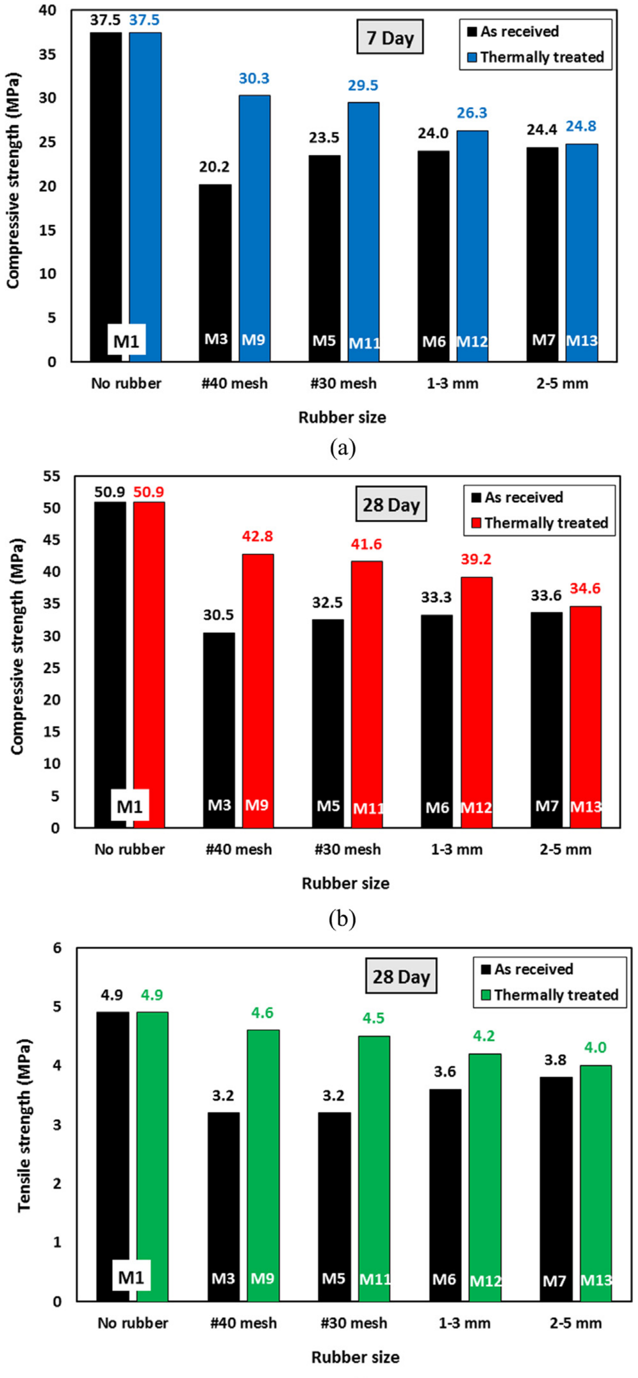


(a)

(b)

(c)

Fig. 6. Effect of thermal treatment at different rubber contents on: (a) Compressive strength at 7 days, (b) Compressive strength at 28 days, and (c) indirect tensile strength at 28 days.



(a)

(b)

(c)

Fig. 7. Effect of thermal treatment at different rubber sizes on: (a) Compressive strength at 7 days, (b) Compressive strength at 28 days, and (c) indirect tensile strength at 28 days.

improving the stiffness of rubber particles with thermal treatment, these weak positions become relatively strong, which slows the rate of strength loss with increasing rubber content. However, this finding should be confirmed by repeating similar analysis for lower strength concrete.

3.3.2. At different rubber sizes

The effects of rubber thermal pre-treatment at different rubber sizes on concrete compressive and tensile strengths were determined through comparison of the results of mixtures M1, M3, M5-M7, M9, and M11-13. This was measured at constant rubber content of 20% and heating time of 1 h, then plotted in Fig. 7. As shown in the figure, similar trends were recorded for compressive strength at both 7 and 28 days. Using as-received rubber size of #40 mesh, decreased the compressive strength by 46% and 40% at 7 days and 28 days, respectively.

Beyond that, as the size of the used rubber's particle increases, the compressive strength shows two opposite trends. In the case of as-received rubber mixtures, the compressive strength losses decrease as the size of the rubber particles increases. For example, increasing the crumb rubber size by using #30 mesh, 1–3 mm, and 2–5 mm, the compressive strength losses were 37%, 36%, and 35%, respectively at 7 days, and 36%, 35%, and 34%, respectively at 28 days. The decrease in compressive strength losses with rubber size increase could be attributed to the increase in the fineness modulus of the hydride aggregates overall (sand and rubber) by increasing the rubber size. Increasing the concrete aggregate's fineness modulus increases its compressive strength [45].

On the other hand, the thermally-treated rubber mixtures showed an enhancement in compressive strength as the size of the rubber particles decreased. For example, increasing the rubber size by using #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm, decreased the compressive strength by 19%, 21%, 30%, and 34%, respectively at 7 days, and by 16%, 18%, 23%, and 32%, respectively at 28 days. The smaller the rubber size, the higher the strength recovery that can be achieved by using the thermal treatment approach. The thermal treatment for rubber recovered 58%, 43%, 17%, and 3% of the compressive strength losses at 7 days, and recovered 60%, 49%, 33%, and 6% at 28 days, respectively when using #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm rubber sizes. This was attributed to the low thermal conductivity of rubber by nature in addition to the increase in rubber size. This decreased the rate of heat transfer from the surface toward the centre of each particle at a given heating time and temperature, hence resulting in less particle stiffness enhancement with rubber size increase. In addition, the larger crumb rubber size (e.g. 2–5 mm rubber size with average particle size of 1.77 mm) has lower overall surface area than that of the smaller rubber size (e.g. #40 mesh rubber size with average particle size of 0.28 mm). This reduces the influence of the thermal treatment approach on enhancing the rubber particles' adhesion to the surrounding cement in concrete, and hence lessens strength recovery.

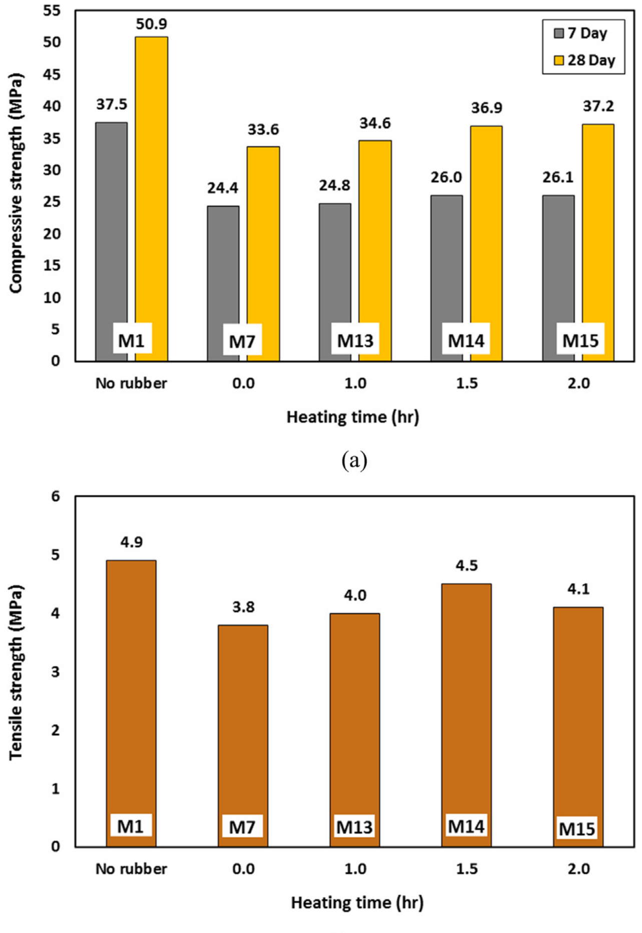
Similar to the corresponding compressive strength at 28 days, the measured indirect tensile strength showed continuous increase and continuous decrease as rubber size increased for as-received and thermally-treated rubber, respectively, as shown in Fig. 7(c). However, less tensile strength losses and higher recovery when using thermally treated rubber were recorded. Using #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm, decreased the indirect tensile strength by 35%, 35%, 26%, and 22%, respectively when using as-received rubber, and by only 6%, 8%, 14%, and 18%, respectively when using thermally treated rubber. The thermal treatment for rubber recovered 82%, 76%, 46%, and 18%, respectively when using #40 mesh, #30 mesh, 1–3 mm, and 2–5 mm rubber sizes. This indicated better performance of the thermally treated rubber in enhancing concrete tensile strength than in enhancing the corresponding compressive strength.

From the above results, it can be concluded that this treatment method has a sensitivity to the rubber size and that the relatively small rubber particles have more potential to contribute to the enhancement of the compressive and tensile strengths.

3.3.3. At different heating times

The effects of rubber thermal pre-treatment at different heating times on concrete compressive and indirect tensile strengths were determined through comparison of the results of mixtures M1 and M13-15. This was measured at constant rubber content of 20%, and rubber size of 2.5 mm, then plotted in Fig. 8. As shown in Fig. 8(a), there was a good correlation between the 7 and 28 day compressive strengths in which the 7 day compressive strength was about 70–74% of the 28 day compressive strength, regardless of the presence of rubber or heating time. This indicated that the proposed thermal treatment approach does not have any negative effect on the cement hydration progress.

Slight increases in CRC compressive strength were recorded with increases in the heating time because the results in Fig. 8 have been taken from the largest rubber size (2–5 mm), which did not show a significant improvement in general similar to the small rubber sizes.



(a)

(b)

Fig. 8. Effect of heating time on: (a) Compressive strength at 7 and 28 days, and (b) indirect tensile strength at 28 days.

Compared to as-received rubber, heating rubber for 1, 1.5, and 2 h, enhanced the compressive strength by 1.6%, 6.6%, and 7.0%, respectively at 7 days, and by 3.0%, 9.8%, and 10.7%, respectively at 28 days. This resulted in achieving relatively higher compressive strength recovery. Treating rubber for a longer time using this thermal approach, allows for better heat transfer from the rubber particle surface toward the rubber particle centre, which enhanced the particle stiffness.

As shown in Fig. 8(b), the measured tensile strength at 28 days showed continuous increase as the heating time increased up to 1.5 h. Beyond that and at heating time of 2 h, the tensile strength decreased. Increasing the heating time to 1 h and 1.5 h, increased the indirect tensile strength by 5.2% and 12.5%, respectively compared to that of as-received rubber. However, at heating time of 2 h, the tensile strength dropped by 8.8% compared with that at 1.5 h, but was still 7.8% higher than that shown by as-received rubber. This indicated again the relatively higher effectiveness of the current rubber pre-treatment method in improving CRC tensile strength, compared to improvement in the corresponding compressive strength.

From the above results, it can be concluded that the highest tensile strength for CRC with rubber size (2–5 mm) is achieved at 1.5 h of thermal treatment. Then with additional heating time the compressive strengths still increase but the tensile stress has showed some loss. This agrees with the hypothesis mentioned in Section 3.2, that the thermal treatment increases the stiffness of rubber particles. That is, with increasing the heating time, the stiffness of rubber particles increases but the ductility decreases. Therefore, the compressive strength continuously increased with heating time but the tensile strength has shown some losses at later stages. It is also recommended for future studies to investigate the effect of the heating time on the smallest crumb rubber size (#40 mesh) as it is expected that the heating time will have significant strength improvements based on the findings in Section 3.3.2.

4. Evaluation of the proposed approach

Several approaches have been established and developed to improve the strength of CRC, e.g. [12–16]. These approaches were mainly directed towards enhancing the rubber particle's surface by water washing, chemical treatments, or coating the rubber particles with different materials. In this section, a comparison between the effectiveness of the currently proposed rubber pre-treatment approach and previously published approaches is carried out to evaluate the proposed thermal approach. This was focused on comparing the recovery at the 28 day CRC compressive strength, which is the main characteristic property of concrete. The compressive strength recovery was determined using Eq. (1) (see Section 1). Table 3 shows the details of this evaluation. In this table, the data were ordered ascendingly based on the rubber content up to 40%, then three rubber content categories (4–10%, 15–20% and 30–40%) were assigned for easy comparison. As shown in the table, it is obvious that the current rubber pre-treatment approach has the highest CRC compressive strength recovery ratio, as it showed 92.7% strength recovery compared to the highest one showed by previous research that was 54.6%. In addition, in each category, the current thermal treatment improvement is still superior compared to others within the same category. At rubber contents of 4–10%, 15–20%, and 30–40%, the rubber thermal pre-treatment showed recovery ratios of 2.0, 1.10, 1.29 times the highest ones showed by previous research within the same categories, respectively.

5. Conclusions

This study describes novel experimental research aimed at improving the mechanical properties of rubberised concrete by thermal treatment of the crumb rubber particles. The morphology of crumb rubber particles before and after thermal treatment was studied and compared. The mechanical properties including compressive and tensile strengths were measured to test the efficiency of the proposed approach. An evaluation of the proposed thermal treatment against previously published rubber pre-treatments was also carried out. The main findings of this investigation are summarised in the following points:

1. Heating the crumb rubber to a relatively high temperature before adding into concrete mixtures results in two main effects: (i) removing many impurities which are found on the crumb rubber surface, and (ii) developing a hard shell on the rubber particle surface. Both effects elevate the interface and stress transfer between rubber particles and concrete. Thermally-treated rubber particles have relatively strong bond with the concrete matrix even after destructive compression tests.
2. The thermal treatment for rubber recovered 93%, 60%, and 47% of the compressive strength losses compared with conventional concrete at 28 days, and recovered 106%, 82%, and 57% of tensile strength losses, respectively when using 10%, 20%, and 40% rubber contents.

Table 3
Comparison of the effectiveness of current and previous rubber pre-treatment approaches.

Pre-treatment method	Rubber Content (Vol %)	Compressive strength			
		Control concrete (MPa)	CRC with as-received rubber (MPa)	CRC with pre-treated rubber (MPa)	Recovery (%)
KMnO4 for 2 h, then NaHso3 for 1 h [57]	4	49.2	23.6	35.1	44.9
Limestone powder pre-coating [14]	5	40.0	34.0	36.5	41.7
Heating for 1 h [Current study]	**10**	**50.9**	**40.0**	**50.1**	**92.7**
Limestone powder pre-coating [14]	10	40.0	30.5	33.0	26.3
CaCl2 for 24 h [27]	15	51.3	37.1	42.3	36.6
MgSO4 for 24 h [27]	15	51.3	37.1	39.5	16.9
Limestone powder pre-coating [14]	15	40.0	25.3	27.5	15.0
Heating for 1 h [Current study]	**20**	**50.9**	**30.5**	**42.8**	**60.3**
NaOH for 30 min [53]	20	53.5	41.6	48.1	54.6
NaOH for 30 min [21]	20	52.0	37.0	42.8	38.7
NaOH for 30 min [17]	20	53.5	35.9	42.1	35.2
NaOH for 24 h [12]	20	55.6	27.0	35.0	28.0
Water soaking for 24 h [16]	20	55.6	27.0	34.9	27.6
Water soaking for 24 h [19]	20	35.4	21.5	24.6	22.3
NaOH for 1 h [17]	20	53.5	35.9	38.6	15.3
NaOH for 2 h [17]	20	53.5	35.9	37.2	7.4
Cement and silane pre-coating [13]	30	38.0	23.0	28.5	36.7
NaOH for 24 h [12]	30	63.0	27.4	31.4	11.2
Water soaking for 24 h [16]	30	63.0	27.4	30.9	9.8
Cement paste pre-coating [15]	38	54.0	32.0	37.0	22.7
Water wash [15]	38	54.0	32.0	33.5	6.8
NaOH for 20 min [15]	38	54.0	32.0	33.0	4.5
Heating for 1 h [Current study]	**40**	**50.9**	**13.7**	**31.3**	**47.3**
Water wash [31]	40	46.8	22.4	26.2	15.6

SF *= Silica Fume* ***NaOH*** *= Sodium Hydroxide.*
$CaCl_2$ *= Calcium chloride* ***$MgSO_4$*** *= Magnesium sulphate.*

3. The thermal treatment method has a sensitivity to the rubber size and the relatively small rubber particles have more potential to contribute to the enhancement of the compressive and tensile strengths.
4. Treating rubber for a longer time using the proposed thermal approach allows for better heat transfer from the rubber particle surface towards the rubber particle centre, which relatively enhanced the particle stiffness. This resulted in achieving relatively higher compressive strength recovery. However, the improvement lessened beyond a heating duration of 1.5 h.
5. The evaluation of the proposed rubber treatment approach showed that it has the highest CRC compressive strength recovery ratio of published pre-treatment methods to date. It showed 92.7% strength recovery compared to the highest one showed by previous research of 54.6%.
6. Although, the current rubber pre-treatment approach could not achieve full strength recovery, CRC still can be employed in many construction applications that do not require high strength concrete (such as residential footings and pavements).

The work in this research proposed a new method to treat rubber and encourage the concrete and construction industry to use more crumb rubber, which benefits the environment.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgment

This research has been undertaken as part of a larger project that has been funded by the Australian Research Council (ARC-LP160100298) and industry partners Tyre Stewardship Australia, FMG Engineering Pty Ltd, Tyrecycle Pty Ltd, ResourceCo Pty Ltd and Ancon Beton, and the authors gratefully acknowledge their support. In addition the authors are grateful for the donation of the following materials: sand and stone (10 mm and 20 mm) by ResourceCo Pty. Ltd., cement by Adelaide Brighton Cement Pty. Ltd., and rubber by Tyrecycle Pty. Ltd. The authors also acknowledge the contributions of Mr. Tom Benn, Mr. Tim Golding, the technical staff team in the School of Natural and Built Environments and the following Honours' students who assisted in the experimental work reported in this paper: Chun Yin Julian Tang, Joel Egel, Longquan Su, Sami Alyami, Ahmad Sahli, Obaid Alharbi, Nasser Alhajri, and Muteb Alsharyah.

References

[1] http://www.wbcsd.org/Projects/Tire-Industry-Project/Resources/End-of-Life-Tires-A-framework-for-effective-management-systems (accessed on 25 Seprember 2017).

[2] F. Brindley, COAG Standing Council on Environment and Water study into domestic and international fate of end-of-life tyres : final report/Fraser Brindley, Emma Mountjoy, Gavin Mountjoy, Hyder Consulting, Melbourne, 2012.

[3] G.S. Kumaran, N. Mushule, M. Lakshmipathy, A review on construction technologies that enables environmental protection: rubberized concrete, Am. J. Eng. Appl. Sci. 1 (1) (2008) 5.

[4] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and portland cement concrete: an overview, Construct. Build. Mater. 67 (Part B) (2014) 217–224.

[5] S. Guo, Q. Dai, R. Si, X. Sun, C. Lu, Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire, J. Cleaner Prod. 148 (Supplement C) (2017) 681–689.

[6] F. Hernández-Olivares, G. Barluenga, M. Bollati, B. Witoszek, Static and dynamic behaviour of recycled tyre rubber-filled concrete, Cem. Concr. Res. 32 (10) (2002) 1587–1596.

[7] T. Gupta, S. Chaudhary, R.K. Sharma, Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate, Construction and Building Materials 73 (Supplement C) (2014) 562–574.

[8] B.S. Thomas, R.C. Gupta, P. Kalla, L. Cseteneyi, Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates, Construct. Build. Mater. 59 (Supplement C) (2014) 204–212.

[9] H. Su, J. Yang, T.-C. Ling, G.S. Ghataora, S. Dirar, Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes, J. Clean. Prod. 91 (Supplement C) (2015) 288–296.

[10] B.S. Thomas, R.C. Gupta, A comprehensive review on the applications of waste tire rubber in cement concrete, Renew. Sustain. Energy Rev. 54 (Supplement C) (2016) 1323–1333.

[11] M. Sienkiewicz, H. Janik, K. Borzędowska-Labuda, J. Kucińska-Lipka, Environmentally friendly polymer-rubber composites obtained from waste tyres: a review, J. Cleaner Prod. 147 (Supplement C) (2017) 560–571.

[12] I. Mohammadi, H. Khabbaz, K. Vessalas, Enhancing mechanical performance of rubberised concrete pavements with sodium hydroxide treatment, Mater. Struct. 49 (3) (2016) 813–827.

[13] Q. Dong, B. Huang, X. Shu, Rubber modified concrete improved by chemically active coating and silane coupling agent, Construct. Build. Mater. 48 (Supplement C) (2013) 116–123.

[14] O. Onuaguluchi, Effects of surface pre-coating and silica fume on crumb rubber-cement matrix interface and cement mortar properties, J. Cleaner Prod. 104 (Supplement C) (2015) 339–345.

[15] K.B. Najim, M.R. Hall, Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC), Mater. Struct. 46 (12) (2013) 2029–2043.

[16] I. Mohammadi, H. Khabbaz, K. Vessalas, In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements, Construct. Build. Mater. 71 (Supplement C) (2014) 456–471.

[17] O. Youssf, J.E. Mills, R. Hassanli, Assessment of the mechanical performance of crumb rubber concrete, Constr. Build. Mater. 125 (2016) 175–183.

[18] D. Li, J. Mills, T. Benn, X. Ma, R. Gravina, Y. Zhuge, Review of the performance of high-strength rubberized concrete and its potential structural applications, Adv. Civil Eng. Mater. 5 (1) (2016) 149–166.

[19] O. Youssf, R. Hassanli, J.E. Mills, M. Abd Elrahman, An experimental investigation of the mechanical performance and structural application of LECA-Rubcrete, Construct. Build. Mater. 175 (2018) 239–253.

[20] B. Huang, X. Shu, J. Cao, A two-staged surface treatment to improve properties of rubber modified cement composites, Constr. Build. Mater. 40 (2013) 270–274.

[21] M. Balaha, A. Badawy, M. Hashish, Effect of using ground waste tire rubber as fine aggregate on the behaviour of concrete mixes, Indian J. Eng. Mater. Sci. 14 (6) (2007) 427.

[22] N.N. Eldin, A.B. Senouci, Rubber-tire particles as concrete aggregate, J. Mater. Civ. Eng. 5 (4) (1993) 478–496.

[23] F. Pelisser, N. Zavarise, T.A. Longo, A.M. Bernardin, Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition, J. Cleaner Prod. 19 (6) (2011) 757–763.

[24] H. Su, J. Yang, G.S. Ghataora, S. Dirar, Surface modified used rubber tyre aggregates: effect on recycled concrete performance, Mag. Concr. Res. 67 (12) (2015) 680–691.

[25] D.M. Hamza, R.H. Ghedan, Effect of rubber treatment on compressive strength and thermal conductivity of modified rubberized concrete, J. Eng. Dev. 15 (4) (2011) 21–29.

[26] N. Deshpande, S.S. Kulkarni, T. Pawar, V. Gunde, Experimental investigation on strength characteristics of concrete using tyre rubber as aggregates in concrete, Int. J. Appl. Eng. Res. Dev. 4 (2) (2014) 97–108.

[27] S. Tian, T. Zhang, Y. Li, Research on modifier and modified process for rubber-particle used in rubberized concrete for road, Adv. Mater. Res. 243–249 (2011) 4125–4130.

[28] G. Li, M.A. Stubblefield, G. Garrick, J. Eggers, C. Abadie, B. Huang, Development of waste tire modified concrete, Cem. Concr. Res. 34 (12) (2004) 2283–2289.

[29] A. Turatsinze, S. Bonnet, J.-L. Granju, Potential of rubber aggregates to modify properties of cement based-mortars: improvement in cracking shrinkage resistance, Constr. Build. Mater. 21 (1) (2007) 176–181.

[30] C. Albano, N. Camacho, J. Reyes, J.L. Feliu, M. Hernández, Influence of scrap rubber addition to Portland I concrete composites: destructive and non-destructive testing, Compos. Struct. 71 (3–4) (2005) 439–446.

[31] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, N.F. Medina, Optimisation of rubberised concrete with high rubber content: an experimental investigation, Constr. Build. Mater. 124 (2016) 391–404.

[32] O. Youssf, R. Hassanli, J.E. Mills, Y. Zhuge, Axial compression behaviour of hybrid double-skin tubular columns filled with rubcrete, J. Compos. Sci. 3 (2) (2019) 62.

[33] O. Youssf, R. Hassanli, J. Mills, X. Ma, Y. Zhuge, Cyclic performance of steel–concrete–steel sandwich beams with rubcrete and LECA concrete core, J. Compos. Sci. 3 (1) (2019) 5.

[34] K.S. Son, I. Hajirasouliha, K. Pilakoutas, Strength and deformability of waste tyre rubber-filled reinforced concrete columns, Constr. Build. Mater. 25 (1) (2011) 218–226.

[35] O. Youssf, M.A. ElGawady, J.E. Mills, Static cyclic behaviour of FRP-confined crumb rubber concrete columns, Eng. Struct. 113 (2016) 371–387.

[36] R. Hassanli, O. Youssf, J.E. Mills, Experimental investigations of reinforced rubberized concrete structural members, J. Build. Eng. 10 (2017) 149–165.

[37] A.G. Bowland, Comparison and Analysis of the Strength, Stiffness, and Damping Characteristics of Concrete with Rubber, Latex, and Carbonate Additives, Virginia Polytechnic Institute and State University, 2011.

[38] O. Youssf, R. Hassanli, J.E. Mills, Retrofitting square columns using FRP-confined crumb rubber concrete to improve confinement efficiency, Construct. Build. Mater. 153 (Supplement C) (2017) 146–156.

[39] N. Ganesan, R. Bharati, A.P. Shashikala, Behavior of self-consolidating rubberized concrete beam-column joints, ACI Mater. J. 110 (6) (2013) 697–704.

[40] R. Hassanli, O. Youssf, J.E. Mills, R. Karim, T. Vincent, Performance of segmental self-centering rubberized concrete columns under different loading directions, J. Build. Eng. 20 (2018) 285–302.

[41] Standards Australia, AS 3972. General purpose and blended cements; 2010.

[42] Standards Australia, Aggregates and rock for engineering purposes – Concrete aggregates, AS 2758.1, 2014.

[43] Standards Australia, AS 1012.2. Methods for testing concrete, Preparation of concrete mixes in the laboratory, 1994.

[44] Standards Australia, Methods for testing concrete, Preparation of concrete mixes in the laboratory AS 1012.2, 2014.

[45] Standards Australia, Methods for sampling and testing aggregates, Method for making and curing concrete – Compression and indirect tensile test specimens, AS1012.8.1, 2014.

[46] Standards Australia, AS 1012.9. Methods for testing concrete, Determination of the compressive strength of concrete specimens, 1999.

[47] Standards Australia, AS 1012.10. Methods of testing concrete Determination of indirect tensile strength of concrete cylinders ('Brasil' or splitting test), 2000.

[48] http://www.scraptirenews.com/crumb.php (accessed on October 2017).

[49] M.K. Batayneh, I. Marie, I. Asi, Promoting the use of crumb rubber concrete in developing countries, Waste Manage. 28 (11) (2008) 2171–2176.

[50] G. Ossola, A. Wojcik, UV modification of tire rubber for use in cementitious composites, Cement Concrete Compos. 52 (Supplement C) (2014) 34–41.

[51] L. He, Y. Ma, Q. Liu, Y. Mu, Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete, Construct. Build. Mater. 120 (Supplement C) (2016) 403–407.

[52] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, N.F. Medina, Optimisation of rubberised concrete with high rubber content: an experimental investigation, Construct. Build. Mater. 124 (Supplement C) (2016) 391–404.

[53] O. Youssf, M.A. ElGawady, J.E. Mills, X. Ma, An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes, Constr. Build. Mater. 53 (2014) 522–532.

[54] O. Youssf, R. Hassanli, J.E. Mills, Mechanical performance of FRP-confined and unconfined crumb rubber concrete containing high rubber content, J. Build. Eng. 11 (2017) 115–126.

[55] F. Aslani, Mechanical properties of waste tire rubber concrete, J. Mater. Civ. Eng. 28 (3) (2015) 04015152.

[56] K.E. Kaloush, G.B. Way, H. Zhu, Properties of crumb rubber concrete, Transp. Res. Rec. 1914 (1) (2005) 8–14.

[57] L. He, Y. Ma, Q. Liu, Y. Mu, Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete, Constr. Build. Mater. 120 (2016) 403–407.