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# **Towards the development of sustainable concrete incorporating waste tyre rubber: A long-term study of physical, mechanical & durability properties and environmental impact**

## **Abstract**

The dramatic increase in the demand for vehicle tyres and consequently the rapid rise in associated waste rubber has been a concern for several decades. Rubber disposal has adverse effects on the environment, human health and a detrimental effect on sustainable development across the world. This paper investigates the effectiveness of a sodium hydroxide treatment method for waste rubber in addition to the utilisation of silica fume to improve the interfacial transition zone between the rubber and cement matrix. This has been shown to have important implication for the long-term development of physical and mechanical properties of concrete aged for 2 years. This study emphasises that while satisfactory improvements are attained through the rubber treatment alone, the actual performance of rubberized concrete containing silica fume could only be investigated over the long term owing to the slow pozzolanic reaction and its dependency on the formation of calcium hydroxide. The pre-treatment of rubber and more specifically the utilisation of silica fume improved the durability of concrete over rubber replacement levels from ~20% to 40%. Long-term thermal conductivity and sound permeability of concrete containing tyre rubber were shown to have important consequences in energy conservation and social sustainability in construction practice. Results reported on the cost efficiency and consequently the CO<sub>2</sub> emissions of concrete containing rubber do not only enhance awareness of the development of sustainable construction materials but also lead a cleaner alternative waste management route for tyre rubber.

## **Keywords**

Waste tyre rubber; reusing; long-term performance; thermal and sound conductivity; cost and carbon efficiency.

Word Count: 8540

## 1. Introduction

The immediate rise in the amount of waste generation, more pronounced with the rapid increase in the population of the world over the last few decades, is threatening the health and environment as well as threatening the sustainable development of the whole planet [1]. Annual worldwide waste generation is projected to rise to 3.4 billion tons by 2050. Nevertheless, the annual tyre production has reached up to 355 million. In Europe that corresponds to nearly 24% of the world's production [2]. Rubbers, account for approximately 48% of the material constituents of tyres and often have adverse impacts on ecology and environmental health when disposed. This is of particular concern in developing countries where improper disposal may occur [3]. Landfilling, for instance, might not only contaminate the soil and underground water due to the non-biodegradability of rubbers, but also results in hazardous situations such as fires and insect proliferation when implemented in uncontrolled environmental sites [2,4,5]. Incineration, on the other hand, emits toxic gases that necessitate expensive treatment and is also impracticable and not cost effective in operation [6].

Incorporation of tyre rubbers in concrete manufacture initiated in 1993 by Eldin and Senoduci [7,8]. Since then, several studies have reported the significant reduction on the engineering properties of concrete when rubbers are used as a cement replacement [9,10]. Although improved mechanical properties are attained to a certain extent when rubber is used as a replacement material for aggregates, this implementation still requires enhancement in many respects [10,11]. Incompatibility of tyre rubbers is the main challenge when used as a mix constituent in concrete. For instance, Tiwari et al. (2016) stated that the lower toughness of rubbers is responsible from the reduced mechanical strength of concrete [12]. Shu and Huang (2014) emphasised that the weak bonds that develop between the smooth surface of rubbers and the cement paste are due mainly to the hydrophobic nature of the rubber material [13]. Roychand et al. (2020) reported the lower relative density of rubber compared to conventional aggregates that significantly decreases the density of concrete [10]. Roychand et al. (2020) also reported the significance of the particle size of the rubbers on determining the mechanical properties of concrete. It is further shown in the study that the rise in the fineness of rubbers, regardless of the replacement level, eventuated in a rise in the engineering properties of concrete [10]. The thermal behaviour of light concrete blocks slabs and joists comprising various amounts of rubber particles from end-of-life tyres was investigated by Fraile-Garcia et al. (2018) [14]. The results from this study revealed that rubber content played a significant role in the determination of the thermal behaviour of concrete elements. Sodupe-Ortega et al. (2018) also exhibited the successful incorporation of crumb rubbers up to 20% as aggregate substitutes in long hollow blocks and bricks [15]. Fraile-Garcia et al. (2016) furthermore, demonstrated that elements comprised higher levels of waste tyre rubbers exhibited excellent performance for isolating low frequency sounds while intermediate and standard elements establish a most remarkable choice for block middle and high frequency sounds. It must be emphasized that in both

conditions, substantial amounts of waste tyre rubbers were recycled in concrete building elements that enhanced environmental sustainability [16].

There are however, several means to compensate the reduction in the engineering properties of concrete containing tyre rubbers. Exposing the rubber particles in alkaline solution prior to the incorporation in concrete is reported to provide enhancements in the mechanical properties of such materials [17]. Although much less in number, there are some studies that incorporated silica fume in concrete along with pre-treated rubbers that report enhanced mechanical properties of these materials due to the better anchorage established among the rubber particles and the cementitious matrix which enabled improved bond development in concrete [17,18]. Although the pre-treatment techniques reported in the literature may exhibit wide diversity, such as basic wash with water [19], to the ultraviolet rays (UV) exposure [20], the most effective method is stated to be the utilisation of an alkali-activator, such as sodium hydroxide (NaOH) solution [21, 22]. The ideal procedure as well as the ideal period of treatment are stated to be achieved by immersing the tyre rubbers in NaOH solution for 30 minutes to attain the required adherence and to strengthen the interface between the rubbers and the cement paste [23,24]. The use of supplementary cementing materials, particularly the utilisation of silica fume, is also reported to improve the interfacial transition zones (ITZ) between the rubbers and the cementitious paste as result of the fine particle size of these materials as well as the pozzolanic activity that enhances the engineering properties and durability of concrete aged for 2 years [25,26]. There are however papers published in the literature that report contentious outputs primarily regarding the pre-treatment effect and the ultimate compressive strength of concrete comprising tyre rubber. Jalal et al. (2019), for instance, report a 30% and 50% strength reduction of concrete when 10 and 15% rubbers were used as a replacement material respectively [27, 28]. Turatsinze et al. (2009), on the other hand, stated that although the restrained shrinkage cracking could be considerably delayed by the presence of 30% rubber aggregates, a substantial decrease attained in strength avoided the use of such materials when high strength is a priority [29]. There are also several studies in the literature that addresses substantial strength reduction in rubberised concrete. Li et al. (2004) and Zaleska et al. (2019) independently reported a reduction of approximately 50% in compressive strength of concrete comprising tyre rubbers as aggregate replacement [30, 31]. Justifiably, different strength results attained in these studies emphasised the necessity of the insight investigations on the authentic performance of tyre rubbers incorporated in concrete.

The other crucial aspects of concrete incorporating tyre rubbers that require comprehensive investigation are the long-term durability, physical properties and mechanical properties. Literature does not address the long-term cost effectiveness along with the CO<sub>2</sub> emissions of concrete containing tyre rubbers thoroughly. The contribution to sound and thermal permeability and therefore the potential of

rubberized concrete in energy conservation and social sustainability has been disregarded to a large extent so far.

It was therefore crucial to investigate the long-term properties of concrete incorporating incremental replacement levels of tyre rubber. The novelty of the study lies in the investigation of the influence of surface treatment of rubber as well as the incorporation of silica fume on the improvement of the interfacial transition zones of concrete aged for 2 years. Replacement levels of tyre rubber were 2.5, 5 and 10% whereas the substitution level of silica fume was 10% throughout the study. Tyre rubber was utilised as a fine aggregate substitute and silica fume was used as a binder substitute in this paper. Following a detailed material characterisation, the influence of the incremental rubber incorporation as well as the effectiveness of the treatment method adopted in this paper on the long-term physical, mechanical and durability properties are studied. Key properties of concrete, including compressive strength, flexural strength, water penetration depth, porosity, resistance to freezing and thawing as well as resistance to sulphate attack, are greatly enhanced by the surface treatment of rubber additions in addition to the incorporation of silica fume. Long-term investigations on the thermal conductivity and sound permeability of concrete containing tyre rubber, provided novelty to the study, and had important influences on energy conservation and social sustainability in construction practice. The results of the long-term cost efficiency and consequently the CO<sub>2</sub> emissions of concrete containing tyre rubber constitutes an original study. It also enhanced awareness of the sustainable and ecological development of construction materials, in particular with high strength.

## **2. Utilisation of Materials and Mixture Design**

The main constituents used for concrete manufacturing were cement binder, fine and coarse aggregates and water. Portland cement used as the primary binder in this study complied with the standard ASTM C150/C150M-16 [32]. Silica fume, utilised as the pozzolanic material was supplied by Cyprus Environmental Enterprises Ltd. (CEE) and complied with the standard ASTM C1240-15 [33]. Waste tyre, used as a partial substitute for sand, were supplied by Rubberland-Kaucuk Ltd. Replacement levels of tyre rubber were 2.5, 5 and 10% whereas the substitution level of silica fume remained constant at 10% by volume in this study. The aggregates were sourced from native rock stocks. The gradations of fine and coarse aggregates, demonstrated in Figure 1, were in compliance with ASTM C136 / C136M-19 [34].

A constant water:binder (w:b) ratio of 0.42 was used for all the concrete mixtures examined in this study. The constant water:binder ratio and consequently similar workability of the investigated mixtures could only be accomplished when replacing fine aggregates with the particle size in the range of 0.25mm to 0.5mm with tyre rubber of the same particle size (particle size retained on 0.25mm and passed through 0.5mm). This was essential to mitigate the discrepancies in the fineness of the raw materials as much as

possible. The substitution level of silica fume was also confined to 10% avoiding inconsistencies in concrete mixtures. These replacement levels and types of both tyre rubber and silica fume were determined to maintain the volume fraction of water:binder ratio in addition to the workability of the concrete identical, as much as possible, without necessitating the additional use of water. This was essential to investigate the sole influences of untreated and treated rubber, as well as silica fume on the short- and long-term properties of concrete. Thereby, the additional influences that would come from the change in water:binder ratio are by-passed. Relatively low water absorption of tyre rubber (0.75%) compared to that of the fine aggregates (2.15%) keep the water demand under control within the mixture during the utilisation of these rubber as sand substitutes ASTM C128 / C128-15 [35]. ACI 211 principles [36], used to obtain the mix constituents of concrete comprising tyre rubber and silica fume, are summarised in Table 1.

Moist duster is used to supply the curing for the first 24 hours following the placement of concrete specimens in moulds. After demoulding the specimens were then located in the cure tanks at a temperature of  $24 \pm 2.0^\circ\text{C}$  to maintain the necessary curing condition till the designated test date. Concrete samples exposed to the freeze and thaw action were stored in the freeze and thaw cabinet and specimens subjected to sulphate attack were placed in potassium sulphate solution for 28, 91, 180, 365 and 730 days.

The tyre rubber in this study were treated using a 1 M sodium hydroxide solution for 30 minutes which is reported to be the most effective treatment method for these materials [8,18,19,37]. Tyre rubber was washed thoroughly to eliminate any contamination from the solution following the chemical treatment. It was also crucial to clean and dry the rubber particles at room temperature before they were incorporated into the concrete.

### **3. Experimental Procedure**

Slump test of freshly mixed concrete was conducted following TS EN 12350-1 [38]. Compressive strength and flexural strength of concrete samples were performed in accordance to TS EN 12390-3 and 12390-5 respectively [39,40]. Three 150mm  $\times$  150mm  $\times$  150mm concrete cube specimens were prepared for compressive strength and three 750mm  $\times$  150mm  $\times$  150mm concrete prism specimens were prepared for flexural strength of each replacement level and treatment type of rubber. Compressive strength tests were conducted on specimens following water curing for periods of 28 days, 3 months, 6 months, 1 year and 2 years. Flexural strength tests, on the other hand, were conducted when the specimens were 28 days and 2 years old. Average compressive and flexural strength values were computed for each group of specimens for all combinations examined in this study. Scanning electron microscopy was used for the microstructural investigations.

Three 150mm × 150mm × 150mm concrete cube specimens were prepared for the measurement of water penetration depth and tested at various ages in accordance to TS EN 12390-8 [41]. Porosity measurements were carried out following the approach stated in ASTM D4404-10 [42].

Resistance to freeze and thaw of concrete was performed [43] using a chamber that completes two consecutive cycles every day. The concrete samples were exposed to curing for 28 days prior to exposure to freeze and thaw. The resistance was evaluated using the compressive strength loss of concrete after completion of 200 uninterrupted cycles. Compressive strength loss was calculated by taking the control compressive strength into account and the compressive strength of concrete exposed to the various treatments/exposures.

External sulphate attack resistance of concrete incorporating tyre rubber was evaluated based on the compressive strength measurements of specimens exposed to sulphate solution. The sulphate solution comprised 50g of Na<sub>2</sub>SO<sub>4</sub> in 1lt of water with a concentration of 352 mole of sodium sulphate (Na<sub>2</sub>SO<sub>4</sub>) per m<sup>3</sup> which complied with ASTM C1012 / C1012M-15 [44]. Similar to the resistance to freezing and thawing, concrete specimens were water cured for 28 days prior to sulphate solution exposure for a further period of 28 days, 3 months, 6 months, 1 year and 2 years. The resistance to external sulphate attack was also examined using the compressive strength of concrete specimens containing tyre rubber.

Three 40mm × 500mm × 500mm concrete prisms were prepared for thermal conductivity and sound permeability evaluation at each replacement level and treatment type of rubber. Thermal conductivity was measured in accordance with TS EN ISO 10456 following specimen water curing for 2 years [45]. Sound permeability of concrete, measured in percentages, was based on the applied and received sound in decibels [46].

Cost efficiency factor (CEF) was determined from the fraction of the compressive strength of concrete to the cost of material used in manufacture per m<sup>3</sup> [47,48,49,50]. The cost of the constituent materials was determined from the local prices of 2021 in North Cyprus in this study.

$$CEF = \frac{F_c}{C} \times 100 \quad (1)$$

Where  $F_c$  is the average compressive strength of concrete and  $C$  is the cost of materials per m<sup>3</sup> of concrete.

Table 2 summarises the cost and CO<sub>2</sub> emissions of the raw materials used in the analysis of cost efficiency factor and calculations of CO<sub>2</sub> emissions respectively. The cost of processing and grinding of tyre rubber, \$31 per ton as well as the cost of rubber treatment, \$9.5 per ton were also taken into account in the CEF.

## **4. Results and Discussion**

### **4.1 Characterisation**

X-ray fluorescence was applied to identify the chemical composition of cement and silica fume used as a binder and a binder replacement, respectively in this study. Table 3 shows that silica fume consists of more than 95% of the summation of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  and hence possess a high pozzolanic index. Chemical composition of cement provided in Table 3 also shows typical distribution of elemental oxides. Physical properties of the raw materials, cement, silica fume and sand, are also summarised in Table 4. High specific surface area of silica fume also re-validates the high fineness of this replacement material and complies with its high pozzolanic activity which is approximately 0.8 in accordance with TS EN13263 [51].

Elemental compositions of tyre rubber before and after the surface treatment, attained from the X-ray fluorescence spectroscopy, are given in Table 5. Tyre rubber, subjected to surface treatment, were soaked in sodium hydroxide solution for 30 minutes and then washed and dried prior to incorporation in the concrete. A slight decrease in the carbon (C) content of treated tyre rubber was noted when compared to the untreated tyre rubber. This could negatively affect the performance of concrete as the carbon-intensive concrete results in a low strength due to the soft nature of carbon. However, the increase in the carbon content obtained following the implementation of the treatment is negligible in this study. Surface treatment of rubber governs the actual performance of concrete by enhancing the adhesion of rubber in concrete. Although the elements of implemented tyre rubber summarised in Table 5 are comparable with the results accredited by Gupta et al. (2015) [52] and Copetti et al. (2020) [18], slight differences in the elemental distributions are attributed to the diversities in the rubber particle production process. The particle size distribution of silica fume, given in a logarithmic axis in microns in Figure 2, validates high fineness compared to the cement. The influence of the surface treatment on the tyre rubber are investigated using petrography analysis. Petrography images with two different magnifications shown in Figures 3a and b for untreated rubber demonstrated a smoother and nearly impervious surface texture compared to that of treated tyre rubber shown in Figures 3c and d. Implementing the treatment method was influential in transforming the surface properties of rubber from smooth to rough and uneven texture that enabled better anchorage to be developed when incorporated in concrete.

### **4.2 Workability**

Workability of the freshly mixed concrete was examined by measuring the slump values prior to the placement of concrete into the standard moulds. The slump values of freshly mixed concrete are presented in Figure 4. Figure 4 shows that the rise in the substitution level of tyre rubber eventuated in a slight reduction in the slump values. This can be attributed to the hydrophobic character of the tyre rubber that may cause slightly stiffer mixtures to be generated. The treatment method adopted to enhance



the interfacial zone among the tyre rubber within the cement paste did not cause any substantial variation in the slump values of fresh concrete, however the incorporation of 10% silica fume led to a small reduction in the slump due to the finer particle size of the pozzolanic material utilised as a substitute to cement in this study. Rise in fineness due to the utilisation of silica fume led to stiffer mixtures being generated and hence a slight reduction in slump. The slump values recorded across the mixtures examined in this study range from 140mm to 162mm. These closed values of slump conform to the implementation of plastic-flowable concrete mixtures in this study. It should be noted that Figure 4 displayed the average slump values of 3 consecutive measurements for each concrete type examined and that the experimental error ranges from 5.5% -7.5% as indicated with the error bars in Figure 4.

### **4.3 Mechanical Properties**

#### **4.3.1 Compressive Strength**

The influence of tyre rubber additions on compressive strength is discussed in this section. Initially, the influence of the treatment method and the utilisation of silica fume on the compressive strength of concrete was investigated using the scanning electron microscopy and then re-examined with respect to curing time periods of concrete.

#### **Incorporation of untreated tyre rubber**

The influence of untreated tyre rubber on the compressive strength of concrete is presented in Figure 5a. The 28<sup>th</sup> day compressive strength of concrete, 50 MPa, is marked as a reference line on the figure. The substitution level of untreated tyre rubber led to a methodical decrease in the compressive strength of concrete at all ages. The compressive strength of concrete incorporating 2.5% of untreated tyre rubber reached 50 MPa and above after 3 months however, it took 2 years for the concrete containing 5% untreated tyre rubber to reach the same reference strength. Concrete incorporating 10% untreated tyre rubber did not reach the reference strength at any of the ages tested. The primary cause for the decrease in the overall compressive strength of concrete comprising untreated tyre rubber is the weak interfacial transition zones that develop between the tyre rubber and the cement paste. The weak, more porous and less consolidated interfacial zones can be attributed to the considerable decrease in compressive strength of the concrete.

It is displayed in Figure 5a that regardless of the substitution level of untreated tyre rubber, the rise in the curing time led to a rise in the compressive strength of concrete due to the continued cure conditions achieved at the laboratory.

#### **Incorporation of treated tyre rubber**

The effect of the surface treatment of rubber on the compressive strength of concrete was investigated. Increasing replacement levels of treated tyre rubber are plotted versus the compressive strength of

concrete in Figure 5b. Similar to the results shown in Figure 5a, rise in the compressive strength of concrete is noticed with the rise in the curing time period due to the continued cure conditions attained at the laboratory. The 28<sup>th</sup> day compressive strength of concrete, 50 MPa, is marked as a reference line on Figure 5b. Figure 5b demonstrated a reduction in the compressive strength of concrete with the rise in the replacement level of treated tyre rubber at all ages. It must be emphasized that the compressive strength of concrete incorporating 2.5% of treated tyre rubber reached 50 MPa soon after 28 days however, it took nearly 3 months for the concrete containing 5% treated tyre rubber to reach the same reference strength. It was also not possible for concrete containing 10% treated tyre rubber to reach the reference strength of 50 MPa at any age tested in the study. It must however be noted that compared to the compressive strength of concrete containing untreated tyre rubber shown in Figure 5a, greater compressive strength results were attained using treated tyre rubber. This clearly indicates that the treatment method had an essential role in increasing the compressive strength of concrete by strengthening the interfacial zones between the tyre rubber and the cement paste. The treatment method allowed surface characteristics of the tyre rubber to be improved and better anchorage to be achieved with the cement paste. These features led to an enhancement in the compressive strength of concrete containing treated tyre rubber.

#### **Incorporation of treated tyre rubber and silica fume**

Although satisfactory compressive strength results were obtained when the tyre rubber were subjected to surface treatment, it was still essential to investigate the alternative routes to further develop the interfacial properties of tyre rubber in concrete, particularly to enable the incorporation of 10% tyre rubber in concrete with high strengths. It was therefore determined to use silica fume, as a substitution to cement to improve adherence of rubber with cement paste, as well as to enhance the physical and mechanical properties of concrete both at short-and long terms.

Figure 5c shows that the utilisation of silica fume along with the treatment of tyre rubber enhanced the compressive strength of concrete significantly and enabled up to 10% tyre rubber to be incorporated in concrete with high strength. Silica fume, a matrix filler material, enabled the development of more consolidated and less porous concrete. The high pozzolanicity of silica fume also promoted pozzolanic reactions with calcium hydroxide from cement hydration leading to the additional generation of calcium-silicate-hydrate gels and consequently further strength gain. As a consequence of the slow pozzolanic reaction, as well as its dependency on the hydration reaction, the authentic impact of silica fume on the compressive strength of concrete incorporating tyre rubber had to be investigated over the long-term.

It should be noted that Figures 5(a-c) exhibited the average compressive strength values of 3 consecutive test results for each replacement level of rubber tyres incorporated in concrete. Experimental error of all

compressive strength results ranged from 3.2% -6.4% and are shown with associated error bars in Figures 5a-c.

Studies by Ganjian et al. (2009) and Pelisser et al. (2011) report the incompatibility of waste rubber utilisation as coarse aggregate substitute mainly as a result of the higher specific gravity of the latter which results in a substantial decrease in the compressive strength of concrete [53, 54]. The studies reported by Richardson et al. (2016), Thomas et al. (2014), Huang et al. (2013) and Khatip and Bayomy (1999) are in agreement with the results of this study as they claimed much lower strength loss due the utilisation of 10% rubber as fine aggregate substitute [55, 56, 57, 58]. On the other hand, the results presented in this paper with respect to the influence of the rubber pre-treatment methods are also in good agreement with Huang et al. (2013) and Pham et al. (2018) [57, 59]. The enhanced compressive strength of concrete attained using the silica fume in conjunction with the rubber pre-treatment methods are also consistent with Copetti et al. (2020) and Raffoul et al. (2016) [18, 60].

Scanning electron microscopy analysis provided an insight into the development of the interfacial transition zones of rubber in cement matrices and consequently the enhancement of compressive strength over both the short- and long-term. It is shown in Figure 6b that surface treatment enhanced the adhesion properties of tyre rubber and promoted improved anchorage development with the cement paste at 28 days compared to concrete containing untreated tyre rubber displayed in Figure 6a. The utilisation of silica fume improved the properties of concrete over both the short- and long-terms. The filler effect of silica fume, shown in Figure 6c resulted in the transformation of the weak interfacial zone to some more consolidated, denser and less porous regions at 28 days that allowed stronger bonds to be developed between the tyre rubber and the cement paste. Silica fume had filled the air pockets in these weak zones and provided denser and stronger transition zones to be developed even over short periods. It is also exhibited in Figure 6d that the utilisation of silica fume further improved the adhesion of rubber in the matrix over the long-term which was mainly responsible from the enhanced concrete strength at 2 years. Scanning electron microscopy analysis shown in Figures 6a-d are in an agreement with the earlier studies [61, 62, 63]. The existence of calcium silicate hydrate (C-S-H) gels, silicate crystals, fly ash and tyre rubber particles of concrete comprising treated tyre rubber at 28 days are highlighted in Figures 6e and f. Scanning electron microscopy images of concrete comprising treated tyre rubber, shown in Figure 6g, exhibited an obvious debonding at the interface between the rubber and the cement matrix at 28 days. Densification of the interfacial transition zone was attributed to the long-term pozzolanic reaction in addition to strengthening of the bond between the rubber particles and newly formed C-S-H gels, as shown in Figure 6h. Pozzolanic concrete comprising treated tyre rubber could only be distinguished at 2 years.

It must also be noted that although one of the objectives of the study is to achieve high strength concrete incorporating waste tyre rubber, it should be emphasized that even the concrete with 10% untreated tyre rubber at 28<sup>th</sup> days provided nearly 30 MPa of a compressive strength which is considerably high for the structural utilisation in construction activities [5]. On the other hand, the application of concrete in practice has a wide spectrum ranging from the use of concrete for backfilling to pavement production and hence the implementation may not always necessitate high strength [64, 65]. Low strength concrete can become an advantage for backfilling where flow-able and controlled density fill are required. Low strength and consequently the improved porosity of concrete can be advantageous to drain water for instance, in gardens and car parks.

### **Influence of curing time on the compressive strength development of concrete incorporating tyre rubber and silica fume**

It is well established that hydration and the pozzolanic reactions are time-dependent. The concrete samples comprising treated tyre rubber and 10% silica fume are only considered here. Figure 7 shows that an increase in curing time, regardless of the replacement level, yields a substantial increase in the concrete compressive strength. Although at a much slower rate, continuation of the hydration reactions even after 28<sup>th</sup> days contributed to the development of the compressive strength of the concrete. Pozzolanic reactions require portlandite produced as a product of the hydration reactions which occur at a slower rate. For this reason, it was necessary to allow the specimens to cure for long-time periods for the actual performance of these materials under compressive stresses to be monitored. It can be seen that even at 2 years, there is still a slight rise in the compressive strength of concrete containing silica fume which validates the persistence of the pozzolanic reaction between silica and the calcium hydroxide.

#### **4.3.2 Flexural Strength**

The flexural strength of concrete incorporating tyre rubber at 28 days and 2 years and corresponding values from the control specimens are presented in Figures 8a and b respectively. Both figures show that irrespective of the treatment method, increasing the rubber substitution levels led to a systematic reduction in the flexural strength at both 28<sup>th</sup> days and 2 years. The decrease in flexural strength was attributed to the weak interfacial zones developed between the rubber particles and cement paste.

Surface treatment of rubber as well as the utilisation of silica fume enriched the interfacial transition zones and consequently improved rubber adhesion to the cement paste thereby increasing the flexural strength. Although the influence of rubber surface treatment is exhibited over the short-term, improvements attributed to silica fume are only observed over the long-term as a consequence of the slower pozzolanic reactions. For instance, Figure 8b shows that higher flexural strength values are noted for concrete incorporating treated rubber and silica fume at 2 years compared to the flexural strength

values at 28 days shown in Figure 8a. It should also be noted that higher flexural strength values of concrete incorporating untreated and treated rubber at 2 years (Figure 8b) are obtained due to the progression of the hydration reaction. Surface treatment of rubber and utilisation of silica fume enabled flexural strength of concrete incorporating 2.5% rubber to reach the reference strength at both 28 days and at 2 years, as shown in Figures 8a and b respectively. Although slightly lower flexural strength values were observed in concrete incorporating 5 and 10% rubber, compared to the reference strength, it should be emphasised that these flexural strength values are sufficiently high for structural use in construction practice.

More importantly, a significant transformation in the failure mode of concrete incorporating tyre rubber was observed. Control specimens showed a sudden and brittle failure when subjected to bending under flexural stresses however, incorporation of rubber enabled a certain amount of deformation to be accommodated leading to a more gradual failure. Compared to the control specimens that exhibited a full disintegration upon failure, increasing the level of small sized rubber substitution improved the matrix cracking resistance and consequently the flexural strength. It should also be noted that the experimental error of all flexural strength values was within the range 4.8% to 6.0% as shown by the error bars in Figures 8a and b. Average flexural strength values, obtained using 3 consecutive test results for each replacement level of rubber tyres incorporated in concrete, are presented in Figures 8a and b.

#### **4.4 Physical Properties**

##### **4.4.1 Water Penetration Depth and Porosity**

Water penetration depth and porosity of concrete comprising tyre rubber was presented in this section. The influence of treatment method in addition to the use of silica fume on water penetration depth and porosity, is illustrated in Figure 9a. Firstly, the results shown in Figure 9a re-established the correlation between the water penetration depth and the concrete porosity at an age of 2 years. The rise in the concrete porosity, irrespective of the rubber substitution level and treatment method led to an increase in the water penetration depth. Concrete manufactured with untreated rubber exhibited the highest porosity at each rubber substitution level and subsequently resulted in the highest water penetration depths. Surface treatment had a greater influence on enhancing the adhesion between the rubber and matrix that enabled denser interfacial transition zones to be generated. This feature considerably reduced the porosity of concrete incorporating treated rubber and as a consequence a proportional reduction in the water penetration depth was observed. The use of silica fume further contributed to the decrease in porosity in addition to the reduction in water penetration depth due to the continued improvement of strength at the interfacial transition zone of rubber in the cement matrix.

Water penetration depth versus porosity of concrete comprising treated tyre rubber with silica fume are shown in Figure 9b. The influence of the time-dependency of the pozzolanic reaction of silica fume as

well as the hydration reaction of cement on the water penetration depth and porosity of concrete are illustrated in Figure 9b. For instance, concrete aged 28 days exhibited the greatest porosity and consequently the greatest water penetration depth at each rubber replacement level. The rise in the curing period clearly exhibited a methodical reduction in concrete porosity at each rubber replacement level and consequently a decrease in water penetration. The concrete specimens incorporating treated tyre rubber and silica fume are used in this section to examine the time dependency of these materials on the water penetration depth and porosity. It must however be noted that despite the higher porosity and water penetration depths obtained, correlative relationships between these parameters existed for concrete with untreated as well as with treated rubber. These findings are also in agreement with previous studies [9,10]. The experimental error of water penetration depth and porosity results did not exceed 5% at all replacement levels and types of rubber incorporated into the concrete and are indicated with the associated error bars in Figures 9a and b.

#### **4.4.2 Mass**

Figure 10 shows the mass and the mass loss (secondary axis) of the concrete specimens incorporating 2.5, 5 and 10% untreated and treated tyre rubber as well as with treated tyre rubber and the inclusion of silica fume. Dry mass of the concrete control specimen at 2 years, shown in Figure 10, was used to calculate the concrete mass loss. All mass measurements were carried out following drying of the specimen in an oven at 105°C for over 24 hours. Figure 10 shows that increasing the level of tyre rubber substitution led to a decrease in concrete mass. For instance, the incorporation of 10% tyre rubber, irrespective of the rubber treatment, caused more than 10% mass loss of concrete. Addition of silica fume further contributed to the rise in the mass loss of the concrete specimens due to the lower bulk density of the pozzolanic material used to replace cement in this study. The decrease in the mass, hence the increase in the mass loss of the specimens have important consequences both in the design stage and at construction phase of concrete in construction practice. 3 consecutive concrete specimens were used to determine the mass of specimens incorporating 2.5, 5 and 10% untreated and treated tyre rubber as well as with treated tyre rubber and the inclusion of silica fume. It should also be noted that the experimental error was within 5% for all replacement levels examined and are shown with associated error bars in Figure 10.

### **4.5 Durability**

#### **4.5.1 Freezing and Thawing Action**

The influence of an increase in substitution level of tyre rubber, as well as the effectiveness of the treatment methods on the resistance to freezing and thawing action on concrete, is presented in this section. To gain an insight into the effects of increasing the replacement level of rubber on the resistance to freezing and thawing action, concrete specimens comprising treated tyre rubber and silica fume were studied. As stated earlier in Section 3, the resistance was evaluated by means of the compressive strength

loss of concrete specimens of varying ages following completion of 200 uninterrupted cycles. The ages of the specimens prior to the freezing and thawing exposure were 28 days, 91 days, 180 days, 365 days and 730 days. Results presented in Figure 11a demonstrate that growth in the substitution level of rubber led to a rise in the compressive strength loss of concrete at all ages examined. The rise in the compressive strength loss is an indication of the decreased resistance attributed to the freeze and thaw action. The positive influences of the treatment method in addition to the aging of specimens on the reduced porosity are well addressed in Section 4. Although the treatment method and increase in the curing time period significantly decreased the overall porosity of the concrete comprising rubber, increase in porosity with the increased replacement level of treated rubber was inevitable due to the incompatibility of the rubber within the cement matrix. Compressive strength loss of the control specimen, shown in the secondary axis in Figure 11a, indicates a good correlation with the compressive strength loss at all ages examined. Smaller compressive strength loss values were obtained for the control specimens mainly due to the more consolidated matrix obtained at all ages. The increase in the curing time period led to a substantial reduction in the compressive strength loss of the concrete indicating an augmented resistance to freeze and thaw action.

The influence of the treatment method on freezing and thawing resistance is studied by taking concrete specimens incorporating 10% of treated rubber into account. Figure 11b shows that concrete incorporating untreated tyre rubber provided the greatest compressive strength loss and hence established the least resistance to freeze and thaw action at all ages examined in the paper. Porosity of concrete incorporating untreated rubber was also exhibited on the secondary axis in Figure 11b. It is evident that the high porosity of these concrete specimens was essentially responsible from the great loss of compressive strength attained due to the physical action of freezing and thawing. Figure 11b shows that porosity of concrete with treated rubber is reduced considerably and also the inclusion of silica fume further contributed in the reduced porosity. This enabled a significant decrease in the compressive strength loss and hence a substantial increase in the resistance to freezing and thawing of concrete with treated tyre rubber and silica fume.

#### **4.5.2 Sulphate Attack**

The resistance of concrete containing incremental replacement levels of rubber to sulphate attack is described in this section. The rise in the replacement level of rubber on the resistance to sulphate attack is studied by taking the concrete specimens containing treated rubber and silica fume only. Figure 12a shows that the rise in the substitution level of rubber led to a methodical increase in the compressive strength loss of concrete at all ages. Like the resistance to freeze and thaw action, an increase in the compressive strength loss in the concrete is an indication of a decrease in the resistance to sulphate attack. The observed reduction in the compressive strength loss of control specimen, exhibited on the secondary axis of Figure 12a, shows a good correlation with the compressive strength loss of concrete

incorporating increased substitution level of rubber with the increase in the curing time period. Consistently, increase in the curing time period also played a key role in decreasing the compressive strength loss and hence enhancing the concrete resistance at all rubber replacement levels.

It is shown in Figure 12b that surface treatment of rubber had a great influence in decreasing the compressive strength loss of concrete and inclusions of silica fume further contributed to this behaviour. Improved adhesion due to the surface treatment of rubber, as well as the filler effect and pozzolanic nature of silica fume, played a vital role. In this case, improving the interfacial transition zone of rubber led to an enhanced resistance of concrete. Water penetration depth values, plotted on the secondary axis, are in agreement with the compressive strength loss of concrete with untreated and treated rubber. Figure 12b shows that the surface treatment of rubber considerably reduced the water penetration depth of concrete reducing the loss in compressive strength attributed to the transportation of sulphate containing fluids into the concrete body. Utilisation of silica fume hindered this transportation due to a decrease in water penetration depth of the concrete and hence improved the resistance to sulphate attack. The results reported in the paper are in good agreement with previously reported findings [66, 67, 68, 69]. 3 consecutive concrete specimens were used to determine the frost and salt resistance of the concrete at each replacement level and type of rubber used as a sand substitute. It should also be noted that the error for these experiments did not exceed 5% at all cases examined in the paper and are shown with associated error bars in Figures 11 and 12.

#### **4.6 Thermal Conductivity and Sound Permeability**

Figures 13a and b present the relationship between porosity and the thermal conductivity and sound permeability of concrete incorporating tyre rubber. The concrete specimens were water-cured for 2 years prior to the thermal conductivity and sound permeability tests. Following removal from the water cure bath they were oven dried at 105°C for 24 hours. The mass reduction was constantly monitored using a top loading balance during drying to ensure steady dry mass was achieved. The samples were then removed from the oven and cooled to room temperature for 1 hour under ambient laboratory conditions (20-25°C and 30-50% RH) before they were subjected to the thermal conductivity and sound permeability measurements. Although the influence of moisture on thermal conductivity and sound permeability of concrete is well established [70, 71], the primary objective of the study was to investigate the influence of the matrix transformation through the rubber pre-treatment in addition to the use of silica fume. The drying procedure adopted prior to the thermal conductivity and sound permeability tests was essential to by-pass additional influences that would come from the presence of moisture within the concrete matrix.

Figure 13a shows that increasing the substitution level of rubber, irrespective of the rubber treatment, leads to a rise in the porosity of concrete that results in a substantial reduction in thermal conductivity.



Concrete with the untreated rubber provided the greatest porosity and hence resulted in the largest reduction in the thermal conductivity at all replacement levels. Surface treatment of rubber as well as the incorporation of silica fume enabled a substantial reduction in porosity that led to a rise the thermal conductivity. Apart from the specimens that contain 2.5% treated rubber and with silica fume, concrete incorporating rubber enabled lower thermal conductivity compared to the control specimen, indicating an enhanced thermal resistivity of these specimens. Incorporation of tyre rubber enables lower thermal conductivity of concrete to be attained and hence greater thermal resistivity to be achieved. This feature has crucial implications in construction practice in terms of identifying innovative development of sustainable construction materials that offer opportunities in energy efficiency in structures as well as in natural energy conservation with the rapid growth in the world's population.

Figure 13b demonstrates the sound permeability of concrete incorporating incremental replacement levels of tyre rubber. Similar to the results exhibited in Figure 13a, it is also shown that increasing the substitution level of rubber, irrespective of the rubber treatment, enabled a rise in the porosity of concrete that further led to a substantial decrease in sound permeability. Concrete containing untreated rubber provided the lowest sound permeability due to the greatest porosity observed at all replacement levels. Surface treatment of rubber as well as the incorporation of silica fume allowed a substantial reduction in porosity of the concrete that led to a considerable rise in the sound permeability. Apart from the specimen that contained 2.5% treated rubber with silica fume, concrete containing rubber enabled lower sound permeability compared to the control specimen, indicating enhanced sound insulation. Incorporation of tyre rubber enables lower sound permeability, greater sound resistivity and sound insulation to be achieved. Use of concrete with low sound permeability and increased sound insulation has a number of applications such as providing acoustic privacy in residential buildings in addition to controlling sounds in commercial settings such as factories and industrial plants. Previously reported studies [72, 73, 74, 75] are in good agreement with the thermal conductivity and sound permeability of concrete incorporating tyre rubber in this paper. 3 consecutive concrete specimens were used to determine the thermal conductivity and sound permeability of concrete at each rubber replacement level. It should also be noted that the error for these experiments did not exceed 5% and is shown with associated error bars in Figure 13.

#### **4.7 Cost Efficiency and CO<sub>2</sub> Emissions**

Cost efficiency and carbon dioxide emissions of concrete incorporating tyre rubber is described in this section. Cost efficiency of concrete incorporating tyre rubber, calculated based on the total cost of the mixture, including the cost of the mix constituents, cost of silica fume, cost of processing and grinding tyre rubber as well as the cost of the surface treatment of rubber, are summarized in Table 6. Short- and long-term cost efficiency of concrete incorporating rubber was calculated by taking into account the 28<sup>th</sup> and 2 years compressive strength of the specimens respectively, as shown in Figure 14a. The control

specimen cost efficiency is indicated by a dashed-line on Figure 14a and used for comparison. It is exhibited in Figure 14a that the cost efficiency of concrete decreased with the rise in the substitution level of rubber due to the corresponding reduction in the compressive strength over the short- and at long-term. It is also shown in Figure 14a that surface treatment of rubber had a determining role in enhancing the cost efficiency due to the improved adhesion of rubber in the matrix and consequently the increased strength of these specimens. Higher compressive strengths of concrete attained at all rubber replacement levels was attributed to the filler effect and the pozzolanic activity of silica fume which improved the cost efficiency of concrete over the long-term.

Cost efficiency of concrete incorporating tyre rubber at 28<sup>th</sup> days are also plotted in this figure for comparison. The trend in cost efficiency of concrete is quite different compared to the 2 year old mortar. For instance, the use of silica fume seems to decrease the cost efficiency of concrete incorporating 10% of treated rubber. As a consequence of the slow reaction of the pozzolanicity as well as its dependency on the formation of calcium hydroxide, the actual performance of silica fume in concrete can only be observed at long-term. The authors emphasize the significance of conducting a long-term study in evaluating the performance of concrete containing tyre rubber meaningfully.

The CO<sub>2</sub> emissions of concrete incorporating tyre rubber, calculated based on the CO<sub>2</sub> emissions of all the mix constituents, as well as the CO<sub>2</sub> emissions of silica fume, are shown in Figure 14b. It is shown in Figure 14b that replacing fine aggregates with tyre rubber does not dramatically decrease the CO<sub>2</sub> emissions mainly as a consequence of the low CO<sub>2</sub> emissions associated with the fine aggregates alone. The reduction in CO<sub>2</sub> emissions of concrete incorporating 10% of silica fume, utilized as a binder substitute, is plotted in the secondary axis in Figure 14b. Significant reduction in CO<sub>2</sub> emissions of concrete comprising silica fume is evident by virtue of the utilization of a low CO<sub>2</sub> emitting replacement material in this paper. It must be emphasized that the use of silica fume, previously shown to enhance all the properties examined in this paper, enabled the implementation of concrete containing tyre rubber to be produced with reduced CO<sub>2</sub> emissions. These results also support the studies previously published in the literature [76].

## **5. Conclusions**

The paper describes an investigation into the effectiveness of pre-treating waste tyre rubber using sodium hydroxide solution for use in concrete. The concrete was also enhanced using additions of silica fume to improve the engineering properties, durability and insulative properties. Improvements in the concrete properties were especially apparent over the long-term. Cost efficiency and CO<sub>2</sub> emissions of concrete containing tyre rubber was also examined in the paper. The findings can be established on the basis of the experimental research outputs:

Increasing the amount of tyre rubber added to the concrete, irrespective of pre-treatment, resulted in a reduction in compressive strength compared to if rubber was not added. Surface pre-treatment of rubber can have a beneficial effect on compressive strength with improvements of approximately 4%, 14% and 24% at 2.5%, 5% and 10% replacement levels of rubber respectively. This improvement on strength was mainly a result of the enhanced adhesion between tyre rubber and the cement paste. The utilization of silica fume further contributed to the development of compressive strength of concrete both over the short- and long-term as a consequence of the filler effect and the high pozzolanicity of the substitute material respectively. The increase in compressive strength was in the range of 14% to 34% depending on the replacement level of treated rubber at 2 years. Experimental results provided in the paper emphasized the transformation of the weak interfacial zone to more consolidated, denser and less porous regions that allowed stronger bonds to be developed between the tyre rubber and the cement paste. This contributed to improved strength and a more consolidated concrete.

The reasons for the enhancement on the flexural strength of concrete incorporating tyre rubber correlated well with those reported for compressive strength. Furthermore, a significant transformation in the failure mode of concrete incorporating tyre rubber was observed. While a sudden and brittle manner of disintegration was observed in the control specimen, incorporation of rubber allowed a certain amount of deformation to take place. This led to a more ductile failure mode attributed to the small sized rubber particles improving the cracking resistance of the matrix and consequently enhancing the concrete flexural strength.

The perfect correlation established between the water penetration depth and the porosity of concrete specimens at an age of 2 years re-validated the precision of the experimental results on the physical properties. The results have shown that while the increase replacement level of tyre rubber had an increasing effect on the water penetration depth and porosity of concrete, surface pre-treatment of rubber and the utilization of silica fume significantly reduced these physical measures and contributed the development of a more consolidated and less porous interfacial transition zones in the matrix. The results have also shown that the mass of concrete significantly condensed with an increase in the substitution level of rubber and inclusion of silica fume.

Correspondingly, the surface pre-treatment of rubber and the utilization of silica fume significantly enhanced the resistance to freezing and thawing and the resistance to sulphate attack of the concrete over the long-term. The physical measures exhibited in the secondary axis of the relevant figures provided insights into the correlation between these properties and the durability of rubberized concrete. For instance, the utilisation of pre-treated tyre rubber and silica fume yielded a reduction of more than 50% on the water penetration depth of the concrete. This was observed for all replacement levels examined in the paper compared to those of the concrete comprising untreated tyre rubber only.

The increase porosity attributed to the substitution of tyre rubber led to a substantial decrease in the thermal conductivity and sound permeability compared to the control specimen. Improved thermal and sound resistivity of concrete containing tyre rubber offered significant consequences in energy conservation and social sustainability in construction practice. The results reported on the cost efficiency and consequently the CO<sub>2</sub> emissions enhanced awareness of the development of sustainable construction materials in particular with high strength.

We recommend that the pre-treatment method proposed for the tyre rubber in the paper can conveniently be implemented in concrete sector as the infrastructure and the technological advances in ready-mix concrete plants are entirely sufficient for the precedent utilisation. The research outputs of this study are of high significance in construction practice due to the improved physical, mechanical and durability properties attained for concrete incorporating treated tyre rubber. The results demonstrate the high potential of using tyre rubber in concrete as a cleaner and greener waste management route compared to the extensively used conventional methods such as land fill or incineration.

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**Figure Captions:**

Figure 1: Grain size distributions of fine and coarse aggregates

Figure 2: Particle size distribution of cement and silica fume

Figure 3: Petrography images of untreated tyre rubbers (a and b) and treated tyre rubbers (c and d)

Figure 4: Slump values of concrete incorporating tyre rubbers

Figure 5: Compressive strength of concrete a; incorporating untreated tyre rubbers, b; incorporating treated tyre rubbers, c; incorporated treated tyre rubbers with silica fume

Figure 6: Scanning electron microscopy images of concrete a; incorporating untreated tyre rubbers at 28 days, b; treated tyre rubbers at 28 days, c; treated tyre rubbers with silica fume at 28 days, d; treated tyre rubbers and silica fume at 2 years, e; treated tyre rubbers at 28 days, f; treated tyre rubbers at 28 days, g; treated tyre rubbers at 28 days, h; treated tyre rubbers at 2 years.

Figure 7: Time dependence of the development of compressive strength of concrete.

Figure 8: Flexural strength of concrete incorporating tyre rubbers a; at 28<sup>th</sup> days, b; at 2 years.

Figure 9a: Water penetration depth versus porosity of concrete a; incorporating tyre rubbers measured at 2 years, b; incorporating treated rubbers and silica fume.

Figure 10: Mass versus the mass loss (%) of concrete incorporating increase replacement level of tyres at 2 years.

Figure 11a: Compressive strength loss of concrete subjected to freezing and thawing action.

Figure 11b: Compressive strength loss versus porosity of concrete incorporating 10% treated rubbers.

Figure 12a: Compressive strength loss of concrete subjected to sulphate attack.

Figure 12b: Compressive strength loss versus porosity of concrete incorporating 10% treated rubbers.

Figure 13a: Thermal conductivity versus porosity of concrete incorporating tyre rubbers.

Figure 13b: Sound permeability versus porosity of concrete incorporating tyre rubbers.

Figure 14a: Cost efficiency of concrete incorporating tyre rubbers.

Figure 14b: CO<sub>2</sub> emissions of concrete incorporating tyre rubbers.

**Table Captions:**

Table 1: Mix constituents

Table 2: The cost and CO<sub>2</sub> emissions of the raw materials

Table 3: Elemental oxide composition of cement and silica fume

Table 4: Physical properties of the raw materials.

Table 5: Elemental composition of tyre rubbers obtained from the X-ray fluorescence spectroscopy

Table 6: Cost efficiency of concrete incorporating waste tyre rubber

## References

- [1] Kaza, S., Yao, L., Bhada-Tata, P., Woerden V.F., 2018. What a waste 2.0: a global snapshot of solid waste management to 2050. The World Bank.
- [2] Torretta, V., Rada, E.C., Ragazzi, M., Trulli, E., Istrate, I. A., Cioca, L.I., 2015. Treatment and disposal of tyres: Two EU approaches: A review. *Waste Management*. 45: 152-160. <https://doi.org/10.1016/j.wasman.2015.04.018>
- [3] Thomas, B.S., Gupta R.C., 2016. A comprehensive review on the applications of waste tire rubber in cement concrete. *Renew. Sust. Energ. Rev.* 54: 1323 - 1333. <https://doi.org/10.1016/j.rser.2015.10.092>
- [4] Dobrotă, D., Dobrotă, G., Dobrescu, T., 2020. Improvement of waste tyre recycling technology based on a new tyre marking. *J. Clean. Prod.* 260: 121141. <https://doi.org/10.1016/j.jclepro.2020.121141>
- [5] Thomas, B.S., Gupta, R.C., 2016. Properties of high strength concrete containing scrap tire rubber. *J. Clean. Prod.* 113:86-92. <https://doi.org/10.1016/j.jclepro.2015.11.019>.
- [6] Gesoğlu, M., Güneyisi, E., 2011. Permeability properties of self-compacting rubberized concretes. *Constr. Build. Mater.* 8:3319-3326. <https://doi.org/10.1016/j.conbuildmat.2011.03.021>.
- [7] Eldin, N.N., & Senouci, A.B., 1993. Rubber-tire particles as concrete aggregate. *J. Mater. Civ. Eng.* 5(4):478-496. [https://doi.org/10.1061/\(ASCE\)0899-1561\(1993\)5:4\(478\)](https://doi.org/10.1061/(ASCE)0899-1561(1993)5:4(478)).
- [8] Guo, H., Yu, Y., Skitmore, M., 2017. Visualization technology-based construction safety management: A review. *Autom. Constr.* 73:135-144. <https://doi.org/10.1016/j.autcon.2016.10.004>.
- [9] Siddika, A., Al Mamun, M.A., Alyousef, R., Amran, Y.M., Aslani, F., Alabduljabbar, H., 2019. Properties and utilizations of waste tire rubber in concrete: A review. *Constr. Build. Mater.* 224:711-731. <https://doi.org/10.1016/j.conbuildmat.2019.07.108>.
- [10] Roychand, R., Gravina, R.J., Zhuge, Y., Ma, X., Youssf, O., Mills, J.E., 2020. A comprehensive review on the mechanical properties of waste tire rubber concrete. *Constr. Build. Mater.* 237: 117651. <https://doi.org/10.1016/j.conbuildmat.2019.117651>.
- [11] Li, N., Long, G., Ma, C., Fu, Q., Zeng, X., Ma, K., Luo, B., 2020. Properties of self-compacting concrete (SCC) with recycled tire rubber aggregate: A comprehensive study. *J. Clean. Prod.* 236:117707. <https://doi.org/10.1016/j.jclepro.2019.117707>.
- [12] Tiwari, A., Singh, S., Nagar, R., 2016. Feasibility assessment for partial replacement of fine aggregate to attain cleaner production perspective in concrete: a review. *J Clean. Prod.* 135:490-507. <https://doi.org/10.1016/j.jclepro.2016.06.130>.
- [13] Shu, X., Huang, B., 2014. Recycling of waste tire rubber in asphalt and Portland cement concrete: an overview. *Constr. Build. Mater.* 67: 217-224. <https://doi.org/10.1016/j.conbuildmat.2013.11.027>.

- [14] Fraile-Garcia, E., Ferreiro-Cabello, J., Mendivil-Giro, M., SanVicente-Navarro, A., 2018. Thermal behaviour of hollow blocks and bricks made of concrete doped with waste tyre rubber. *Constr. Build. Mater.* 176: 193-200. <https://doi.org/10.1016/j.conbuildmat.2018.05.015>.
- [15] Sodupe-Ortega, E., Fraile-Garcia, E., Ferreiro-Cabello, J., Sanz-Garcia, A., 2016. Evaluation of crumb rubber as aggregate for automated manufacturing of rubberized long hollow blocks and bricks. *Constr. Build. Mater.* 106: 305-316. <https://doi.org/10.1016/j.conbuildmat.2015.12.131>.
- [16] Fraile-Garcia, E., Ferreiro-Cabello, F., Defez, B., Peris-Fajanes, G, 2016. Acoustic behavior of hollow blocks and bricks made of concrete doped with waste-tire rubber. *Mater.* 9: 962. [10.3390/ma9120962](https://doi.org/10.3390/ma9120962).
- [17] Chou, L.H., Lu, C.K., Chang, J.R., Lee, M.T., 2007. Use of waste rubber as concrete additive. *Waste Manag. Res.* 1:68-76. <https://doi.org/10.1177/0734242X07067448>.
- [18] Copetti, C.M., Borges, P.M., Squiavon, J.Z, da Silva, S.R., de Oliveira Andrade, J.J., 2020. Evaluation of tire rubber surface pre-treatment and silica fume on physical-mechanical behaviour and microstructural properties of concrete. *J. Clean. Prod.* 256: 120670. <https://doi.org/10.1016/j.jclepro.2020.120670>.
- [19] Pelisser, F., Zavarise, N., Longo, T.A., Bernardin, A.M., 2011. Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition. *J. Clean. Prod.* 19 (6-7): 757-763. <https://doi.org/10.1016/j.jclepro.2010.11.014>.
- [20] Aslani, F, Ma G, Wan, D.L.Y., Le, V.X.T., 2018. Experimental investigation into rubber granules and their effects on the fresh and hardened properties of self-compacting concrete. *J. Clean. Prod.* 172:1835-1847. <https://doi.org/10.1016/j.jclepro.2017.12.003>.
- [21] Shanmugharaj, A.M., Kim, J.K., Ryu, S.H., 2006. Modification of rubber surface by UV surface grafting. *Appl. Surf. Sci.* 16:5714-5722. <https://doi.org/10.1016/j.apsusc.2005.07.069>.
- [22] Polydorou, T., Constantinides, G., Neocleous, K., Kyriakides, N., Koutsokeras, L., Chrysostomou, C., Hadjimitsis, D., 2020. Effects of pre-treatment using waste quarry dust on the adherence of recycled tyre rubber particles to cementitious paste in rubberised concrete. *Constr. Build. Mater.* 254: 119325. <https://doi.org/10.1016/j.conbuildmat.2020.119325>.
- [23] Elchalakani, M., 2015. High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers. *Structures*, 1:20-38. <https://doi.org/10.1016/j.istruc.2014.06.001>.
- [24] Youssf, O., Mills, J.E., Hassanli, R., 2016. Assessment of the mechanical performance of crumb rubber concrete. *Constr. Build. Mater.* 125:175-183. <https://doi.org/10.1016/j.conbuildmat.2016.08.040>.

- [25] Kashani, A., Ngo, T.D., Mendis, P., Black, J.R., Hajimohammadi, A.A., 2017. Sustainable application of recycled tyre crumbs as insulator in lightweight cellular concrete. *J. Clean. Prod.* 149:925-935. <https://doi.org/10.1016/j.jclepro.2017.02.154>.
- [26] Onuaguluchi, O., Panesar, D.K., 2014. Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. *J. Clean. Prod.* 82:125-131. <https://doi.org/10.1016/j.jclepro.2014.06.068>.
- [27] Jalal, M., Nassir, N., Jalal, H., 2019. Waste tire rubber and pozzolans in concrete: A trade-off between cleaner production and mechanical properties in a greener concrete. *J. Clean. Prod.* 238: 117882. <https://doi.org/10.1016/j.jclepro.2019.117882>.
- [28] Tian, S., Zhang, T., & Li, Y., 2011. Research on modifier and modified process for rubber-particle used in rubberized concrete for road. *Adv. Mater, Res*, 243:4125-4130. <https://doi.org/10.4028/www.scientific.net/AMR.243-249.4125>
- [29] Turatsinze, A., Bonnet, S., & Granju, J.L., 2007. Potential of rubber aggregates to modify properties of cement based-mortars: improvement in cracking shrinkage resistance. *Constr. Build. Mater.* 21 (1):176-181. <https://doi.org/10.1016/j.conbuildmat.2005.06.036>.
- [30] Li, G., Stubblefield, M.A., Garrick, G., Eggers, J., Abadie, C., Huang, B., 2004. Development of waste tire modified concrete. *Cem. Concr. Res.* 12:2283-2289. <https://doi.org/10.1016/j.cemconres.2004.04.013>.
- [31] Záleská, M., Pavlík, Z., Čítek, D., Jankovský, O., Pavlíková, M., 2019. Eco-friendly concrete with scrap-tyre-rubber-based aggregate—Properties and thermal stability. *Constr. Build. Mater.* 225:709-722. <https://doi.org/10.1016/j.conbuildmat.2019.07.168>.
- [32] ASTM C150 / C150M-16, 2016. Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA.
- [33] ASTM C1240-15, 2015. Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, West Conshohocken, PA.
- [34] ASTM C136 / C136M-19, 2019. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA.
- [35] ASTM C128 / C128-15, 2019. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, ASTM International, West Conshohocken, PA.
- [36] ACI Committee. 2009. ACI 211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.
- [37] Si, R., Guo, S., Dai, Q., 2017. Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles. *Constr. Build. Mater.* 153:496-505. <https://doi.org/10.1016/j.conbuildmat.2017.07.085>.
- [38] TS EN 12350-1, 2019. Testing fresh concrete - Part 1: Sampling and common apparatus.
- [39] TS EN 12390-3, 2019. Testing hardened concrete - Part 3: Compressive strength of test specimens.



- [40] TS EN 12390-5, 2019. Testing hardened concrete - Part 5: Flexural strength of test specimens.
- [41] TS EN 12390-8, 2019. Testing hardened concrete - Part 8: Depth of penetration of water under pressure.
- [42] ASTM D4404-10, 2010. Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry, ASTM International, West Conshohocken, PA.
- [43] ASTM C666 / C666M-15, 2015. Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, West Conshohocken, PA.
- [44] ASTM C1012 / C1012M-15, 2015. Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution, ASTM International, West Conshohocken, PA.
- [45] TS EN ISO 10456, 2009. Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values.
- [46] TS EN ISO 16283-1, 2014. Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation (ISO 16283-1:2014).
- [47] Agarwal, S.K., & Gulati, D., 2006. Utilization of industrial wastes and unprocessed micro-fillers for making cost effective mortars. *Constr. Build. Mater.* 10: 999-1004.  
<https://doi.org/10.1016/j.conbuildmat.2005.06.009>
- [48] Ince, C., 2020. Reusing gold-mine tailings in cement mortars: Mechanical properties and socio-economic developments for the Lefke-Xeros area of Cyprus. *J. Clean. Prod.* 238:117871.  
<https://doi.org/10.1016/j.jclepro.2019.117871>
- [49] Arel, H.Ş., 2016. Recyclability of waste marble in concrete production. *J. Cleaner. Prod.* 131:179-88. <https://doi.org/10.1016/j.jclepro.2016.05.052>.
- [50] Kim, T., Tae, S., & Roh, S., 2013. Assessment of the CO<sub>2</sub> emission and cost reduction performance of a low-carbon-emission concrete mix design using an optimal mix design system. *Renew. Sust. Ener. Rev.* 25:729-41. <https://doi.org/10.1016/j.rser.2013.05.013>
- [51] TS EN 13263-1, 2010. Silica fume for concrete - Part 1: Definitions, requirements and conformity criteria.
- [52] Gupta, T., Chaudhary, S., Sharma, R.K., 2015. Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. *J. Clean. Prod.* 112:702-711.  
<https://doi.org/10.1016/j.jclepro.2015.07.081>.
- [53] Ganjiana, E., Khoramib, M., Maghsoudic, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr. Build. Mater.* 23 (5): 1828-1836.  
<https://doi.org/10.1016/j.conbuildmat.2008.09.020>.
- [54] Pelisser, F., Barcelos, A., Santos, D., Peterson, M., Bernardin, A.M., 2012. Lightweight concrete production with low Portland cement consumption. *J. Clean. Prod.* 23 (1): 68-74.  
<https://doi.org/10.1016/j.jclepro.2011.10.010>

- [54] Pelisser F, Barcelos A, Santos D, Peterson M, Bernardin A.M. Lightweight concrete production with low Portland cement consumption. *J. Clean. Prod.* 23 (1):68-74.  
<https://doi.org/10.1016/j.jclepro.2011.10.010>
- [55] Richardson, A., Coventry, K., Edmondson, V., Dias, E., 2016. Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size), *J. Clean. Prod.* 112: 599-606.  
[https://doi.org/10.1016/j.jclepro.2015.08.028.](https://doi.org/10.1016/j.jclepro.2015.08.028)
- [56] Warren-Thomas, E., Dolman, P.M., Edwards, D.P., 2015. Increasing Demand for Natural Rubber Necessitates a Robust Sustainability Initiative to Mitigate Impacts on Tropical Biodiversity. *Conservation Letters*, 8: 230-241. <https://doi.org/10.1111/conl.12170>
- [57] Huang, B., Xiang, S., Cao, J., 2013. A two-staged surface treatment to improve properties of rubber modified cement composites. *Constr. Build. Mater.* 40: 270-274.  
<https://doi.org/10.1016/j.conbuildmat.2012.11.014>
- [58] Khatib, Z.K., and Bayomy, F.M., 1999. Rubberized Portland Cement Concrete. *J. Mater. Civ. Eng.* 11 (3). [https://doi.org/10.1061/\(ASCE\)0899-1561\(1999\)11:3\(206\).](https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(206))
- [59] Pham, T.M., Chen, W., Elchalakani, M., Karrech, A., Haoa, H., 2020. Experimental investigation on lightweight rubberized concrete beams strengthened with BFRP sheets subjected to impact loads. *Engin. Struc.* 205: 110095. <https://doi.org/10.1016/j.engstruct.2019.110095>
- [60] Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M., Medina, N.F., 2016. Optimisation of rubberised concrete with high rubber content: An experimental investigation. *Constr. Build. Mater.* 124: 391- 404. [https://doi.org/10.1016/j.conbuildmat.2016.07.054.](https://doi.org/10.1016/j.conbuildmat.2016.07.054)
- [61] Shen, Y., Huang, J., Ma, X., Hao, F., Lv, J., 2020. Experimental study on the free shrinkage of lightweight polymer concrete incorporating waste rubber powder and ceramsite. *Compos. Struct.* 242: 112152. [https://doi.org/10.1016/j.compstruct.2020.112152.](https://doi.org/10.1016/j.compstruct.2020.112152)
- [62] Li, Y, Zhang, S, Wang, R., Dang, F., 2019. Potential use of waste tire rubber as aggregate in cement concrete—A comprehensive review. *Constr. Build. Mater.* 225: 1183-201.
- [63] Kashani, A., Ngot, T.D., Hemachandr, P., Hajimohammadi, A., 2018. Effects of surface treatments of recycled tyre crumb on cement-rubber bonding in concrete composite foam. *Constr. Build. Mater.* 171:467-473. [https://doi.org/10.1016/j.conbuildmat.2018.03.163.](https://doi.org/10.1016/j.conbuildmat.2018.03.163)
- [64] Arulrajah, A., Mohammadinia, A., Maghool, F., Horpibulsuk, S., 2019. Tire derived aggregates as a supplementary material with recycled demolition concrete for pavement applications. *J. Clean. Prod.* 230:129-136. [https://doi.org/10.1016/j.jclepro.2019.05.084.](https://doi.org/10.1016/j.jclepro.2019.05.084)
- [65] Rashid, K., Yazdanbakhsh, A., Rehman, M.U., 2019. Sustainable selection of the concrete incorporating recycled tire aggregate to be used as medium to low strength material. *J. Clean. Prod.* 224:396-410. [https://doi.org/10.1016/j.jclepro.2019.03.197.](https://doi.org/10.1016/j.jclepro.2019.03.197)
- [66] Thomas, B.S., Gupta, R.C., Panicker, V.J., 2016. Recycling of waste tire rubber as aggregate in concrete: durability-related performance. *J. Clean. Prod.* 112:504-513.

<https://doi.org/10.1016/j.jclepro.2015.08.046>

- [67] Bravo, M., De Brito, J., 2012. Concrete made with used tyre aggregate: durability-related performance. *J. Clean. Prod.* 25:42-50. <https://doi.org/10.1016/j.jclepro.2011.11.066>.
- [68] Rahimi, S., Nikbin, I.M., Allahyari, H., Habibi, S., 2016. Sustainable approach for recycling waste tire rubber and polyethylene terephthalate (PET) to produce green concrete with resistance against sulfuric acid attack. *J. Clean. Prod.* 126:166-177. <https://doi.org/10.1016/j.jclepro.2016.03.074>.
- [69] Fernández-Ruiz, M.A., Gil-Martín, L.M., Carbonell-Márquez, J.F., Hernández-Montes, E., 2018. Epoxy resin and ground tyre rubber replacement for cement in concrete: Compressive behaviour and durability properties. *Constr. Build. Mater.* 173:49-57.
- [70] Taoukil, D., El bouardi, A., Sick, F., Mimet, A., Ezbakhe, H., Ajzoul, T. 2013. Moisture content influence on the thermal conductivity and diffusivity of wood–concrete composite. *Constr. Build. Mater.* 48: 104-115. <https://doi.org/10.1016/j.conbuildmat.2013.06.067>.
- [71] Mňahončáková, E., Jiříčková, M., Pavlík, Z. et al. 2006. Effect of Moisture on the Thermal Conductivity of a Cementitious Composite. *International Journal of Thermophysics*, 27, 1228–1240. <https://doi.org/10.1007/s10765-006-0073-y>.
- [72] Kashani, A., Ngo, T.D., Mendis, P., Black, J.R., Hajimohammadi, A.A., 2017. Sustainable application of recycled tyre crumbs as insulator in lightweight cellular concrete. *J. Clean. Prod.* 149:925-935. <https://doi.org/10.1016/j.jclepro.2017.02.154>
- [73] Medina, N. F., Flores-Medina, D., Hernández-Olivares, F., 2016. Influence of fibers partially coated with rubber from tire recycling as aggregate on the acoustical properties of rubberized concrete. *Constr. Build. Mater.* 129:25-36. <https://doi.org/10.1016/j.conbuildmat.2016.11.007>.
- [74] Eijk, V.D.J., Kosten, C.W., Kok, W., 1950. Sound absorption by porous materials I. *Appl. Sci. Res. Section B*, 1:50-62. <https://doi.org/10.1007/BF02919928>.
- [75] Shafigh, P., Asadi, I., Mahyuddin, N.B., 2018. Concrete as a thermal mass material for building applications-A review. *J. Build. Eng.* 19:14-25. <https://doi.org/10.1016/j.jobbe.2018.04.021>.
- [76] Wang, Q.Z., Wang, N.N., Tseng, M.L., Huang, Y.M., Li, N.L., 2020. Waste tire recycling assessment: Road application potential and carbon emissions reduction analysis of crumb rubber modified asphalt in China. *J. Clean. Prod.* 249:119411. <https://doi.org/10.1016/j.jclepro.2019.119411>.

Table 1: Mix constituents

Mixture name	Tyre Rubber (% by volume)	Silica Fume (% by volume)	w/c ratio	Constituents (kg)					
				Water	Cement	Tyre Rubber	Silica Fume	Fine Aggregate	Coarse Aggregate
Control	0	0	0.42	193	459.5	0	0	602	1104
2.5% tyre rubber	2.5	0	0.42	193	459.5	6.34	0	586.95	1104
5% tyre rubber	5	0	0.42	193	459.5	12.68	0	571.9	1104
10% tyre rubber	10	0	0.42	193	459.5	25.37	0	541.8	1104
2.5% tyre rubber + 10%SF	2.5	10	0.42	193	413.5	6.34	25.6	586.95	1104
5% tyre rubber + 10%SF	5	10	0.42	193	413.5	12.68	25.6	571.9	1104
10% tyre rubber + 10%SF	10	10	0.42	193	413.5	25.37	25.6	541.8	1104

Table 2: The cost and CO<sub>2</sub> emissions of the raw materials

Raw Materials	Cost	CO <sub>2</sub> emissions
Cement	\$0.12/kg	0.94 ton-CO <sub>2</sub> /ton [45]
Silica fume	\$0.21/kg	0.014 ton-CO <sub>2</sub> /t (EPA)
Fine aggregate	\$14.86 per m <sup>3</sup>	0.08 kg-CO <sub>2</sub> /m <sup>3</sup> [46]
Coarse aggregate	\$13.85 per m <sup>3</sup>	0.08 kg-CO <sub>2</sub> /m <sup>3</sup> [46]

Table 3: Elemental oxide composition of cement, silica fume and sand

Chemical Composition	Cement (wt%) (ASTM C150/C150M-16)	Silica Fume (wt%) (ASTM C1240-15)	Sand (wt%) (TS EN 196-1)
CaO	43.8	1.25	0.43
ZnO	0.01	0.02	-
SiO <sub>2</sub>	30.2	93.3	92.4
Al <sub>2</sub> O <sub>3</sub>	11.4	0.73	3.75
Fe <sub>2</sub> O <sub>3</sub>	5.11	1.82	0.71
SO <sub>3</sub>	3.29	0.22	0.04
MgO	2.61	0.89	0.12
K <sub>2</sub> O	1.34	1.21	0.94
TiO <sub>2</sub>	0.74	-	0.77
Na <sub>2</sub> O	0.51	0.28	0.45
MnO	0.43	0.09	0.03
Cl	0.03	0.04	0.02

Table 4: Physical properties of the raw materials.

Property	Cement	Silica fume	Sand
Blaine specific surface area (cm <sup>2</sup> /g)	3610	18270	-
Specific gravity	3.15	2.7	2.67
Loss on ignition (wt%)	2.88	4.91	-
Insoluble residue (wt%)	0.31	0.59	-

Table 5: Elemental composition of tyre rubbers obtained from the X-ray fluorescence spectroscopy

Component	Untreated Tyre Rubbers (wt%)	Treated Tyre Rubbers (wt%)
C	50.4	59.5
Fe	6.7	0.3
Zn	1.76	0.02
Si	0.4	0.1
Al	0.02	-
S	0.7	1.8
O	37.4	35.6
P	0.08	0.04
K	0.04	-
Br	0.05	-
Al	0.02	-

Table 6: Cost efficiency of concrete incorporating waste tyre rubber

Cost efficiency of concrete incorporated untreated tyre rubber																
Mix		Mix Constituents					Mix Cost					CEF				
Untreated Rubber Replacement level (%)	Silica Fume Replacement level (%)	Cement (kg)	Fine aggregate (m <sup>3</sup> )	Coarse aggregate (m <sup>3</sup> )	Silica fume (kg)	Tyre rubber (kg)	Cement (\$)	Fine aggregate (\$)	Coarse aggregate (\$)	Silica fume (\$)	Tyre rubber (\$)	$f_{c28d}$	$f_{c2y}$	Cost/m <sup>3</sup> (\$)	CEF <sub>28d}</sub>	CEF <sub>2y</sub>
0	0	459.5	0.232	0.414	0	0	55.14	3.48	5.73	0	0	50.43	65.05	64.35	78.37	101.09
2.5	0	459.5	0.224	0.414	0	6.34	55.14	3.33	5.73	0	0.19	45.15	58.93	64.39	70.12	91.52
5	0	459.5	0.218	0.414	0	12.68	55.14	3.24	5.73	0	0.39	38.03	50.08	64.5	58.96	77.64
10	0	459.5	0.206	0.414	0	25.37	55.14	3.06	5.73	0	0.78	27.96	37.59	64.71	43.21	58.09
Cost efficiency of concrete incorporated treated tyre rubber																
Mix		Mix Constituents					Mix Cost					CEF				
Untreated Rubber Replacement level (%)	Silica Fume Replacement level (%)	Cement (kg)	Fine aggregate (m <sup>3</sup> )	Coarse aggregate (m <sup>3</sup> )	Silica fume (kg)	Tyre rubber (kg)	Cement (\$)	Fine aggregate (\$)	Coarse aggregate (\$)	Silica fume (\$)	Tyre rubber (\$)	$f_{c28d}$	$f_{c2y}$	Cost/m <sup>3</sup> (\$)	CEF <sub>28d}</sub>	CEF <sub>2y</sub>
0	0	459.5	0.232	0.414	0	0	55.14	3.48	5.73	0	0	50.43	65.05	64.35	78.37	101.09
2.5	0	459.5	0.224	0.414	0	6.34	55.14	3.33	5.73	0	0.25	47.55	62.45	64.45	73.78	96.90
5	0	459.5	0.218	0.414	0	12.68	55.14	3.24	5.73	0	0.45	42.89	56.31	64.56	66.43	87.22
10	0	459.5	0.206	0.414	0	25.37	55.14	3.06	5.73	0	0.84	34.33	45.98	64.77	53.00	70.99
Cost efficiency of concrete incorporated treated tyre rubber and silica fume																
Mix		Mix Constituents					Mix Cost					CEF				
Untreated Rubber Replacement level (%)	Silica Fume Replacement level (%)	Cement (kg)	Fine aggregate (m <sup>3</sup> )	Coarse aggregate (m <sup>3</sup> )	Silica fume (kg)	Tyre rubber (kg)	Cement (\$)	Fine aggregate (\$)	Coarse aggregate (\$)	Silica fume (\$)	Tyre rubber (\$)	$f_{c28d}$	$f_{c2y}$	Cost/m <sup>3</sup> (\$)	CEF <sub>28d}</sub>	CEF <sub>2y</sub>
0	0	459.5	0.232	0.414	0	0	55.14	3.48	5.73	0	0	50.43	65.05	64.35	78.37	101.09
2.5	10	413.5	0.224	0.414	25.6	6.34	49.62	3.33	5.73	5.37	0.25	44.76	66.14	64.3	69.61	102.86
5	10	413.5	0.218	0.414	25.6	12.68	49.62	3.24	5.73	5.37	0.45	39.01	58.53	64.41	60.57	90.87
10	10	413.5	0.206	0.414	25.6	25.37	49.62	3.06	5.73	5.37	0.84	31.86	50.69	64.62	49.30	78.44

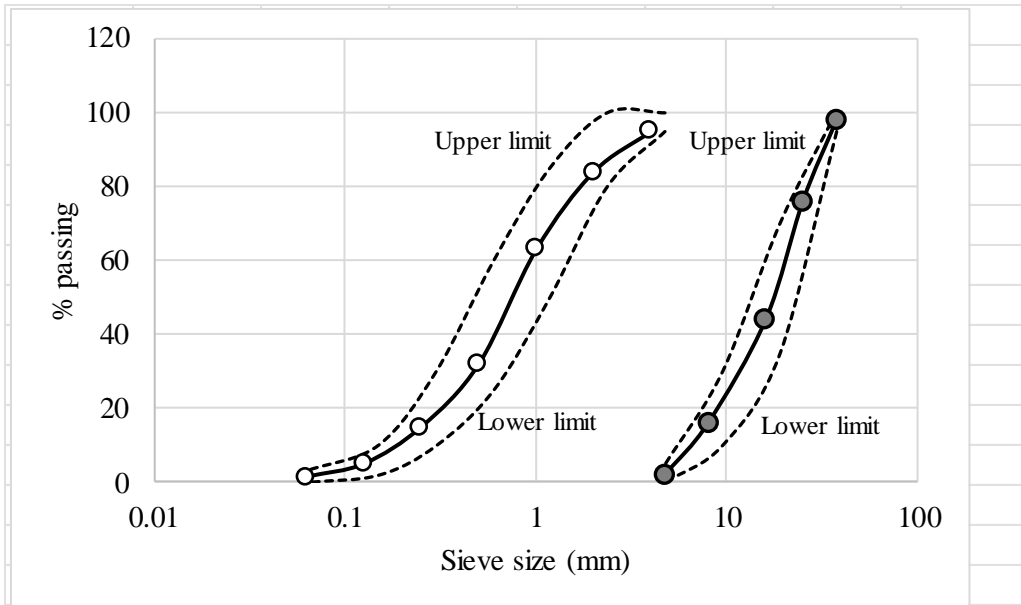


Figure 1

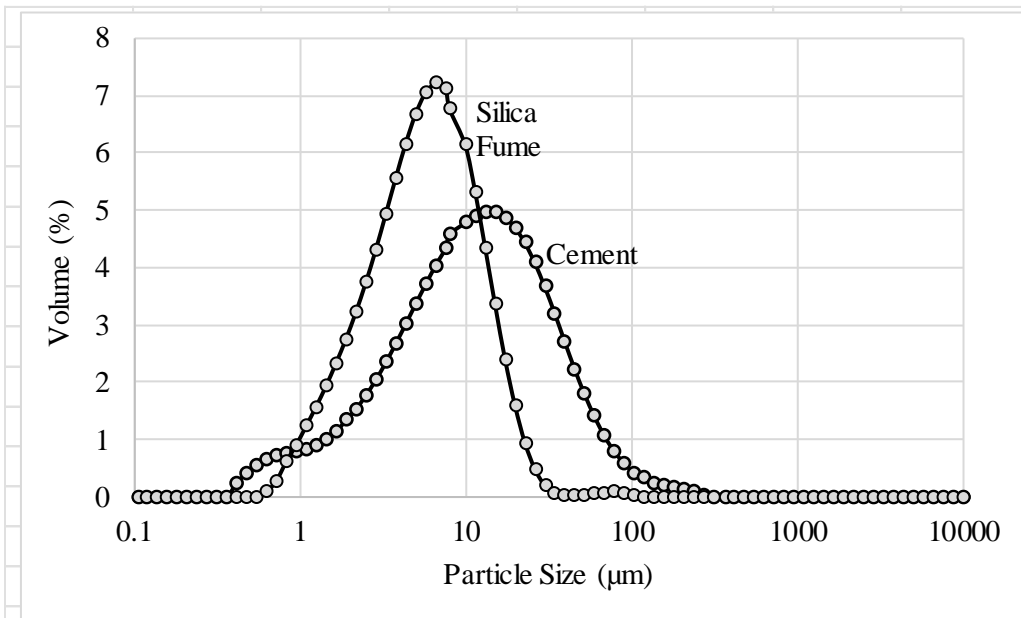
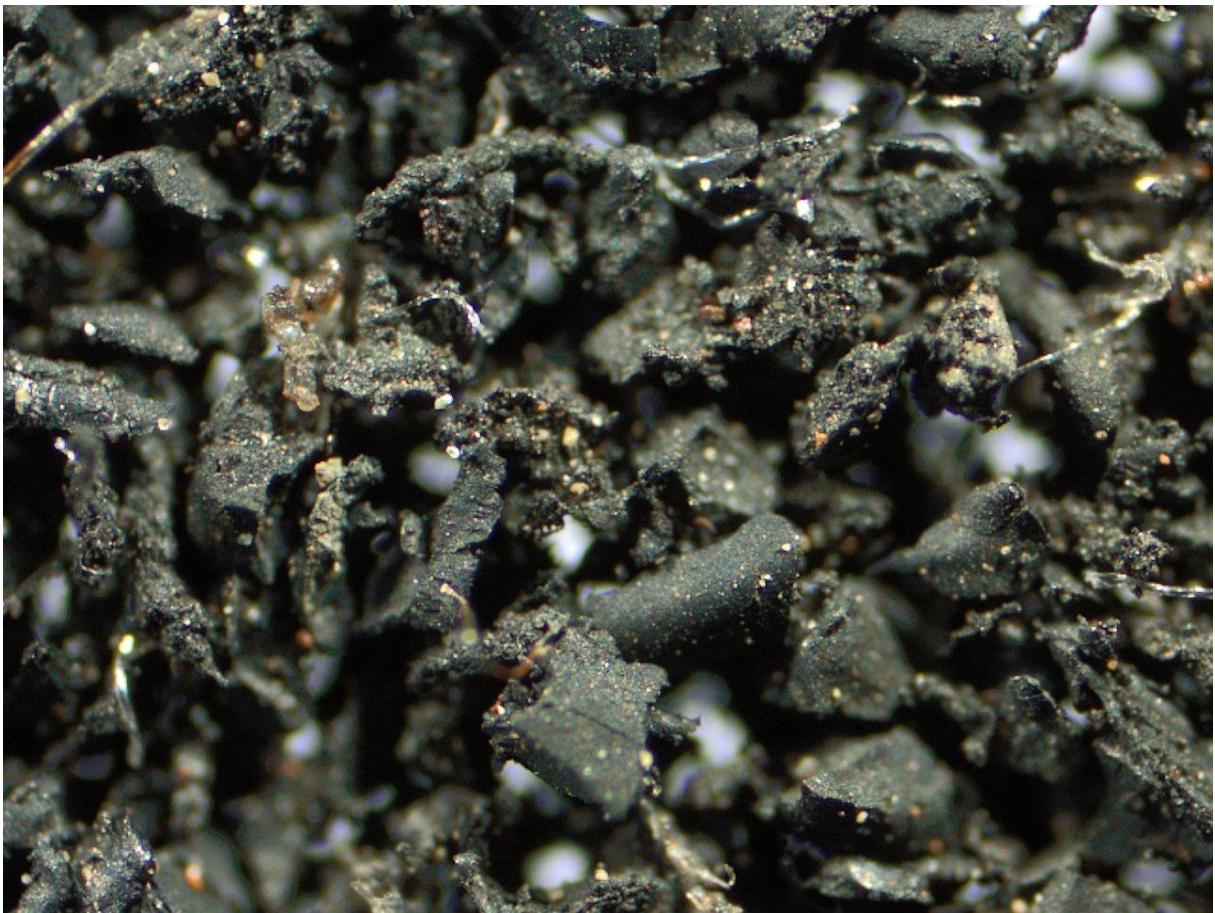
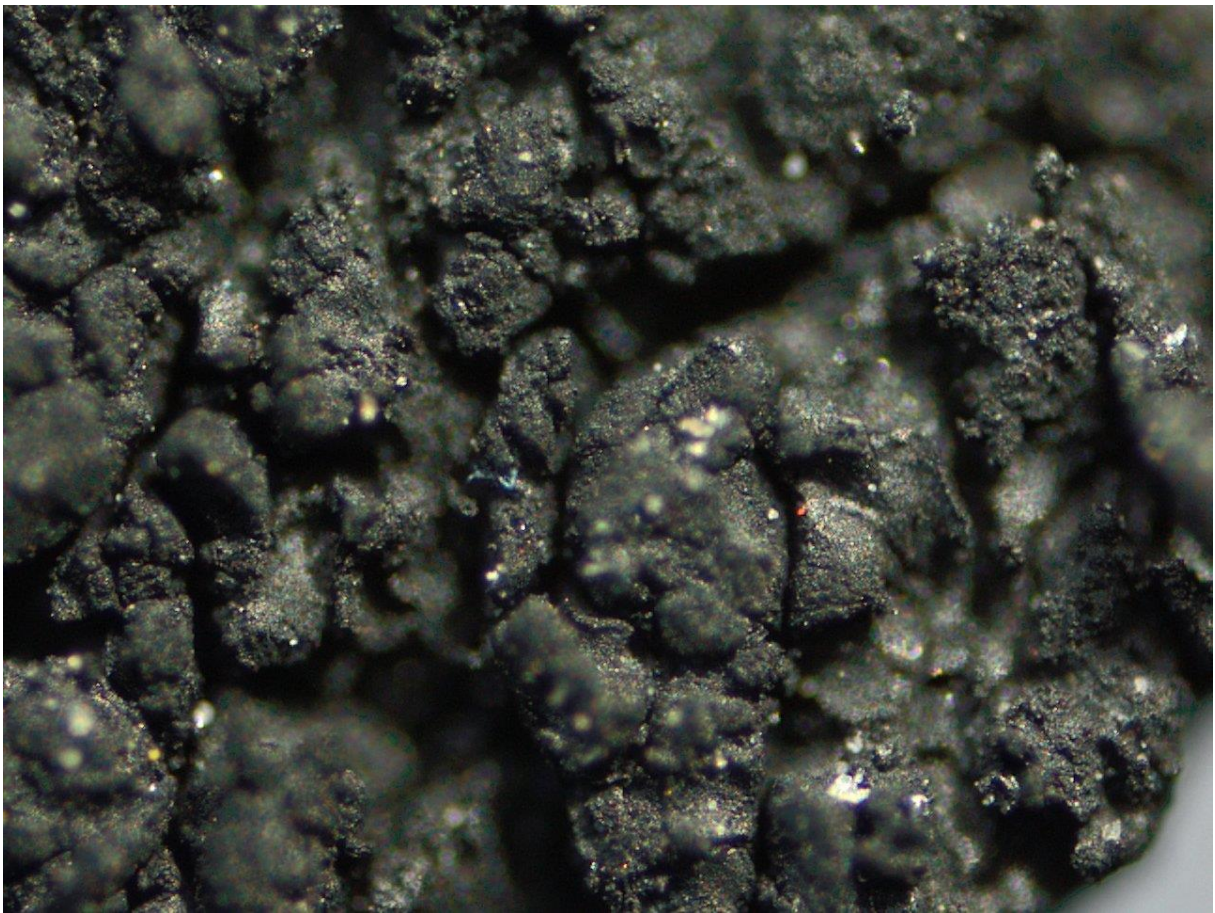


Figure 2











Figures 3a to d

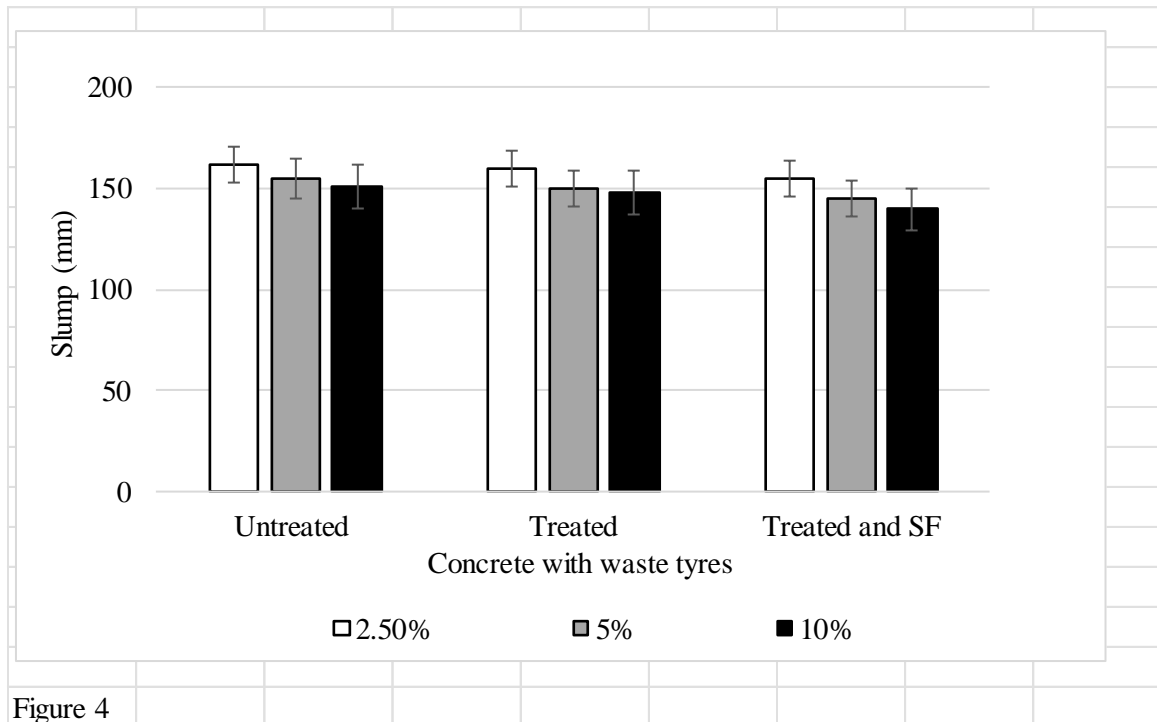


Figure 4

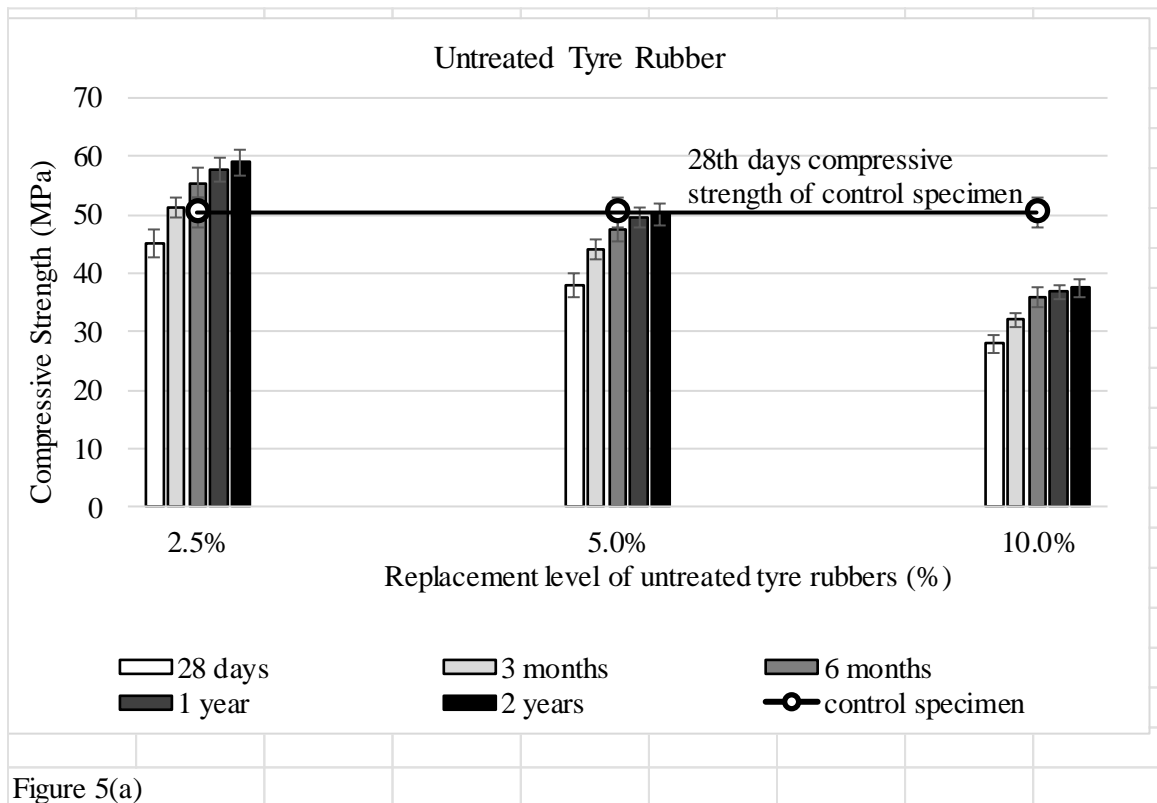


Figure 5(a)

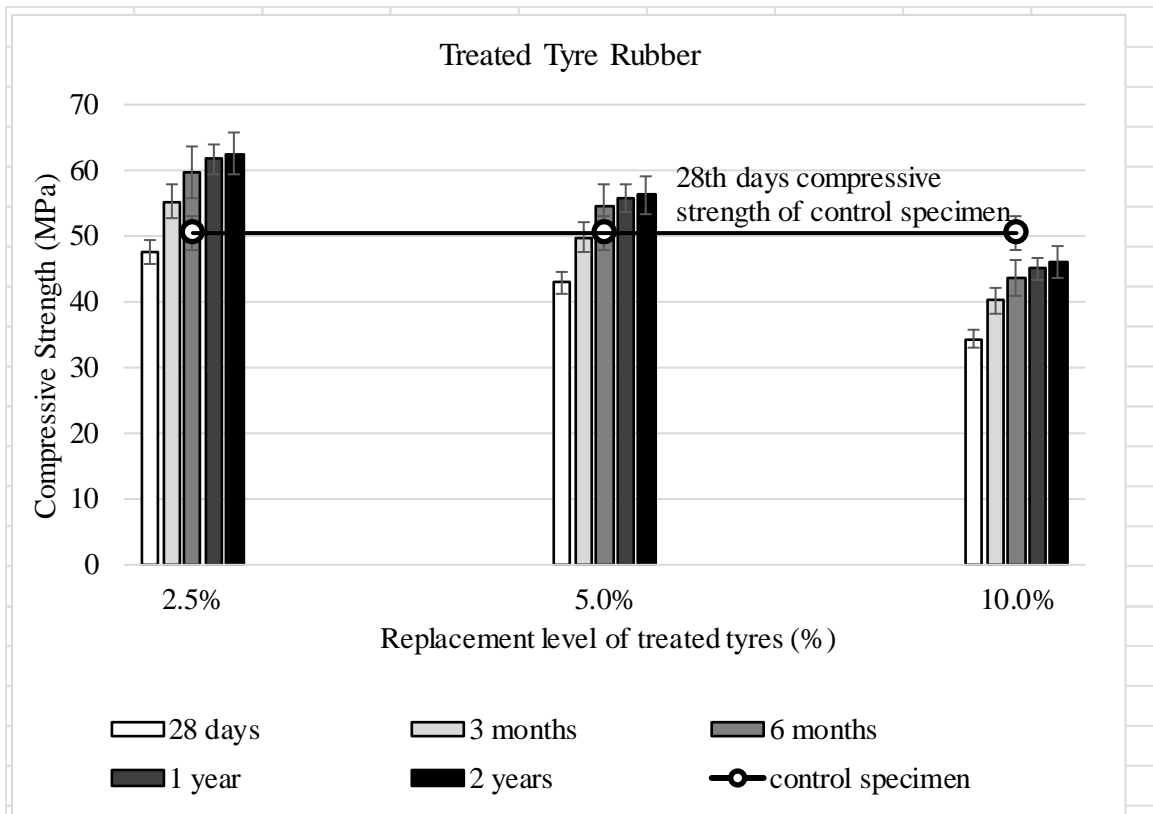


Figure 5b

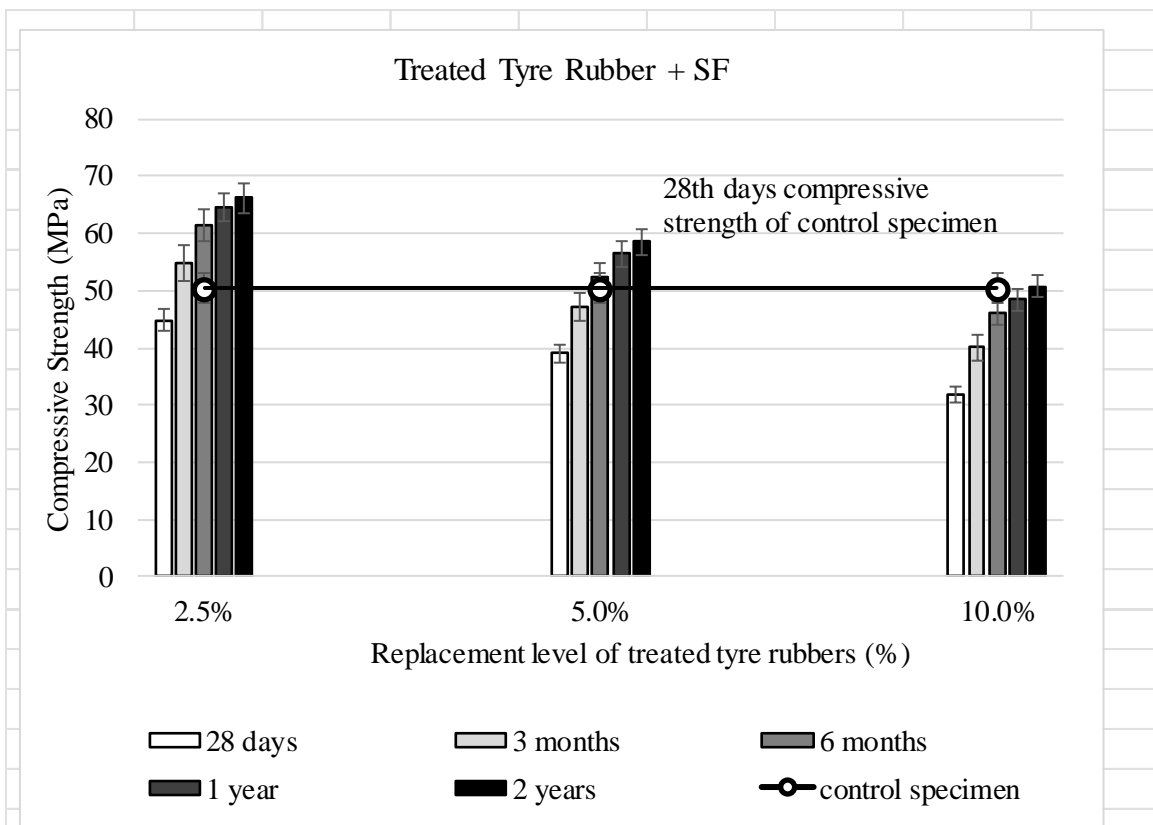


Figure 5(c)

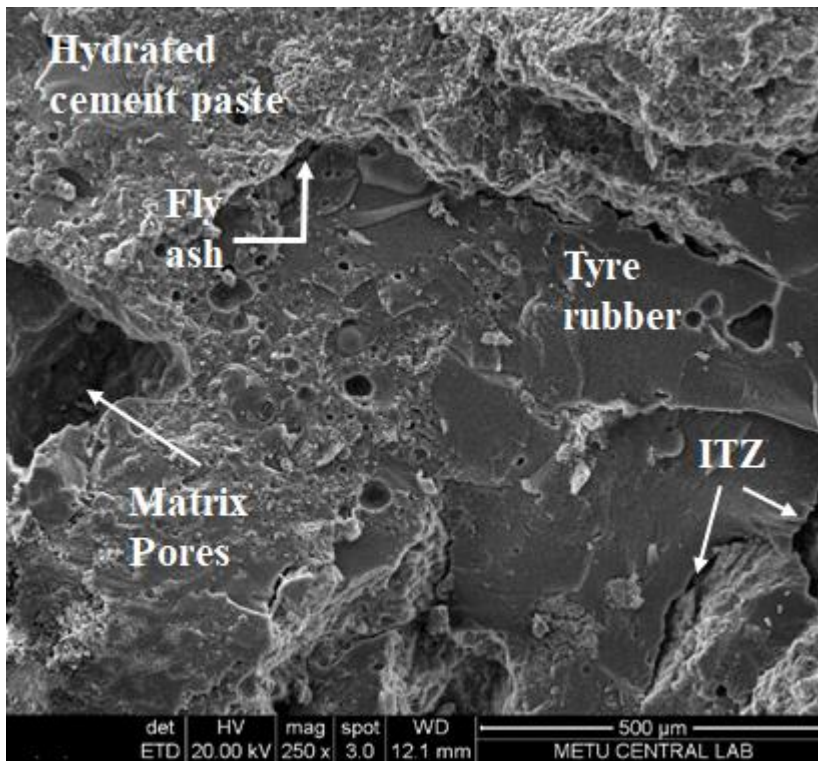


Figure 6a:

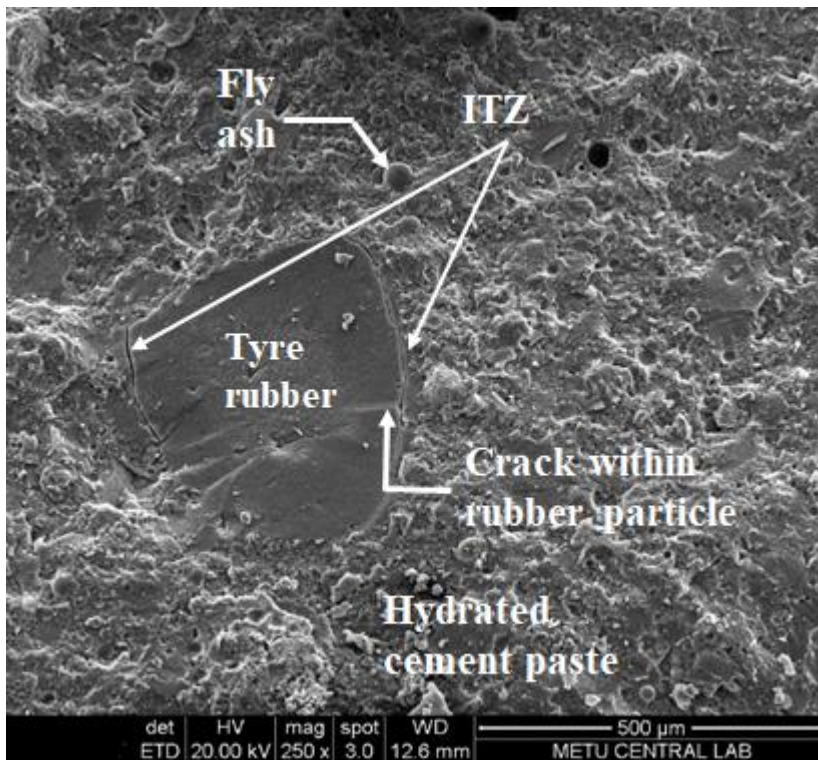


Figure 6b:

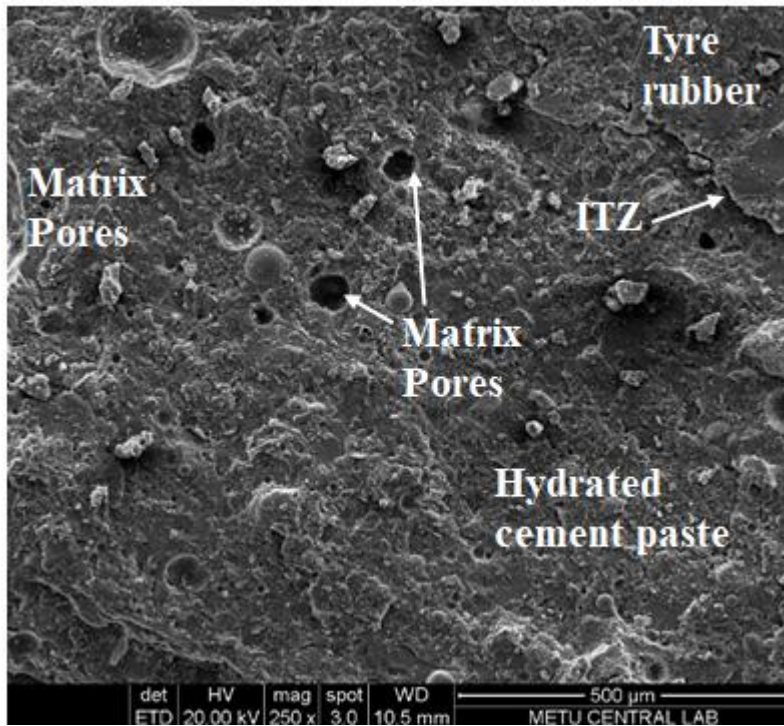


Figure 6c:

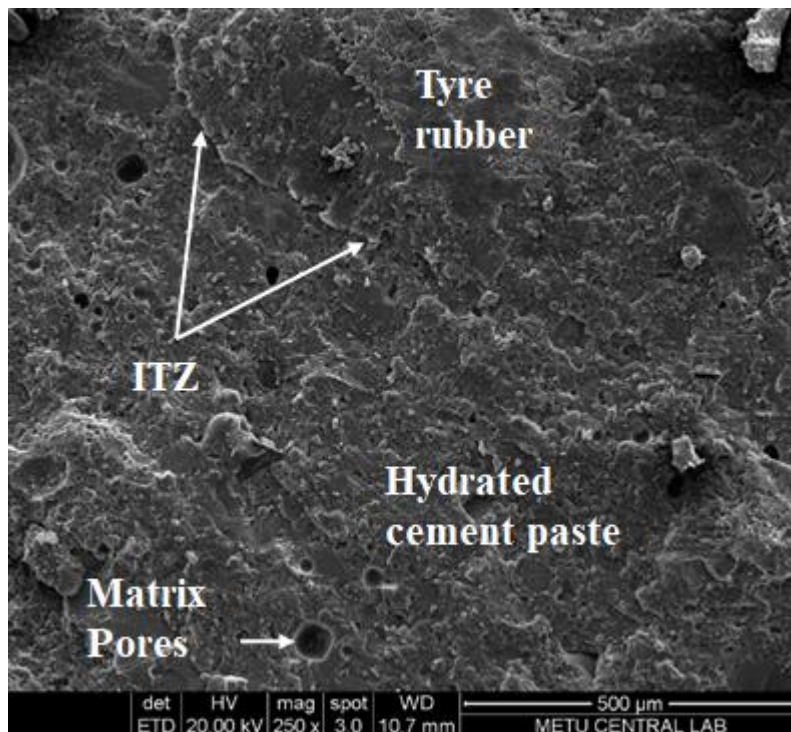


Figure 6d:



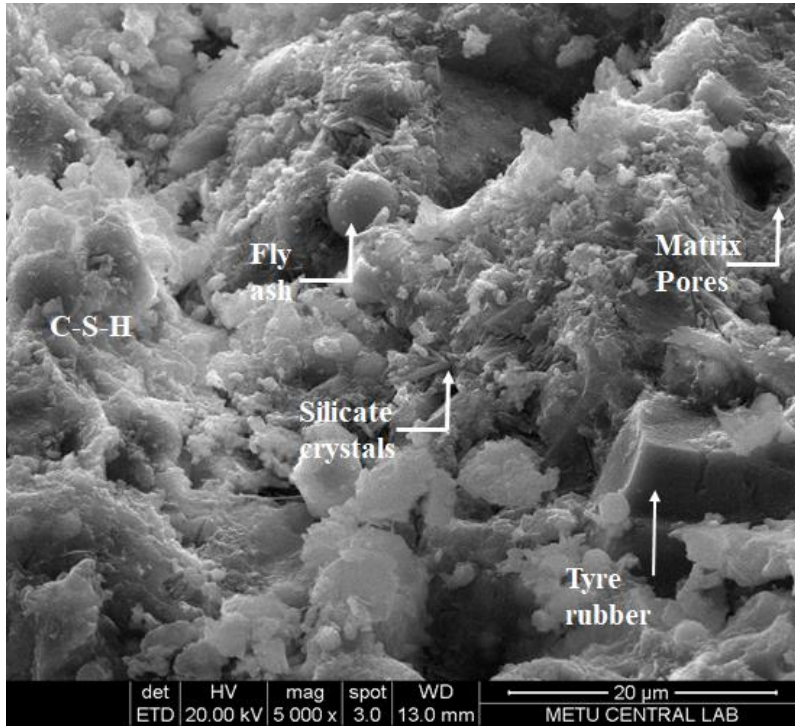


Figure 6e:



Figure 6f:

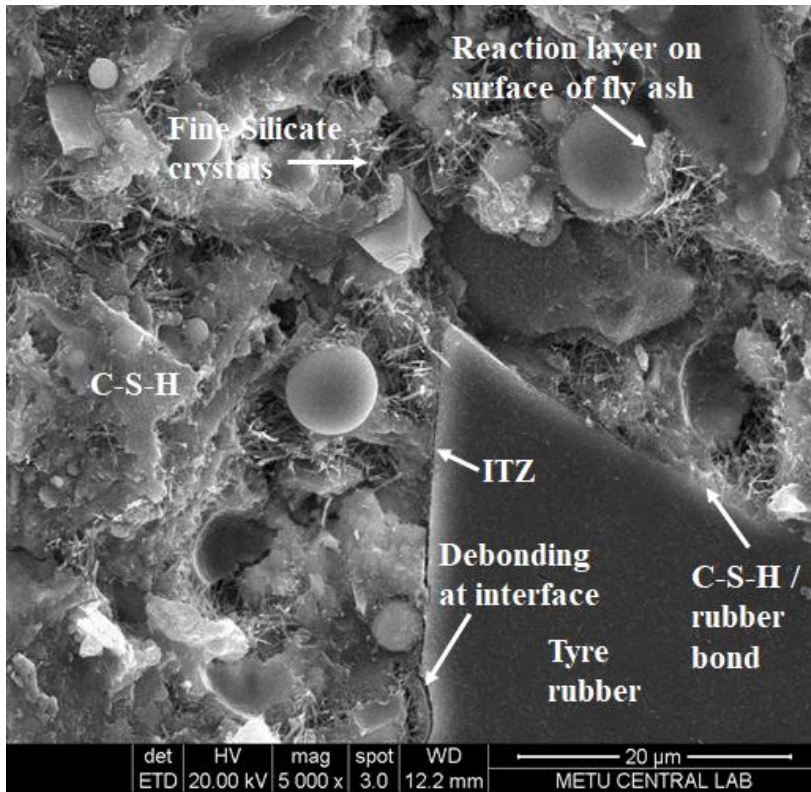


Figure 6g:

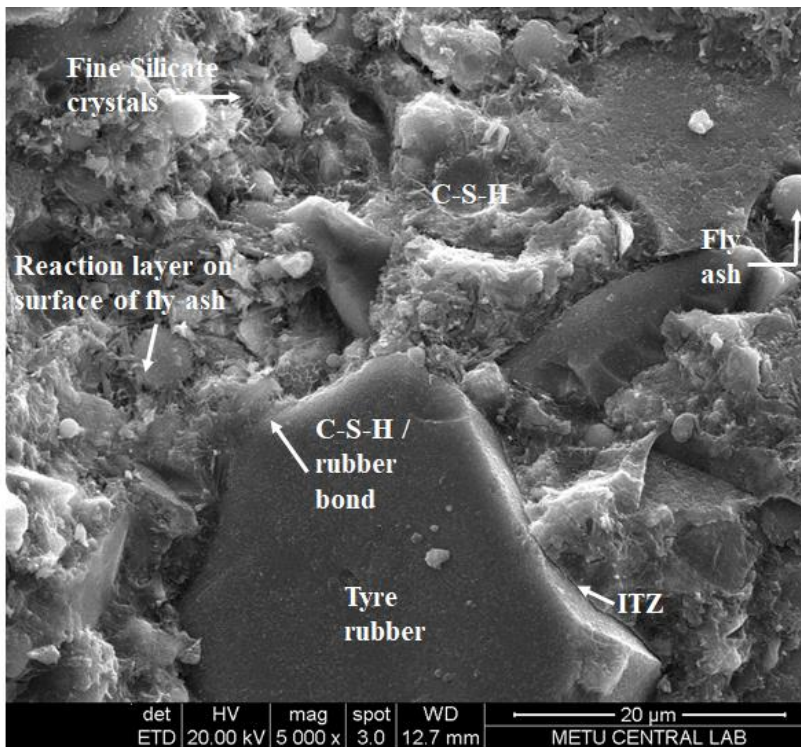


Figure 6h:

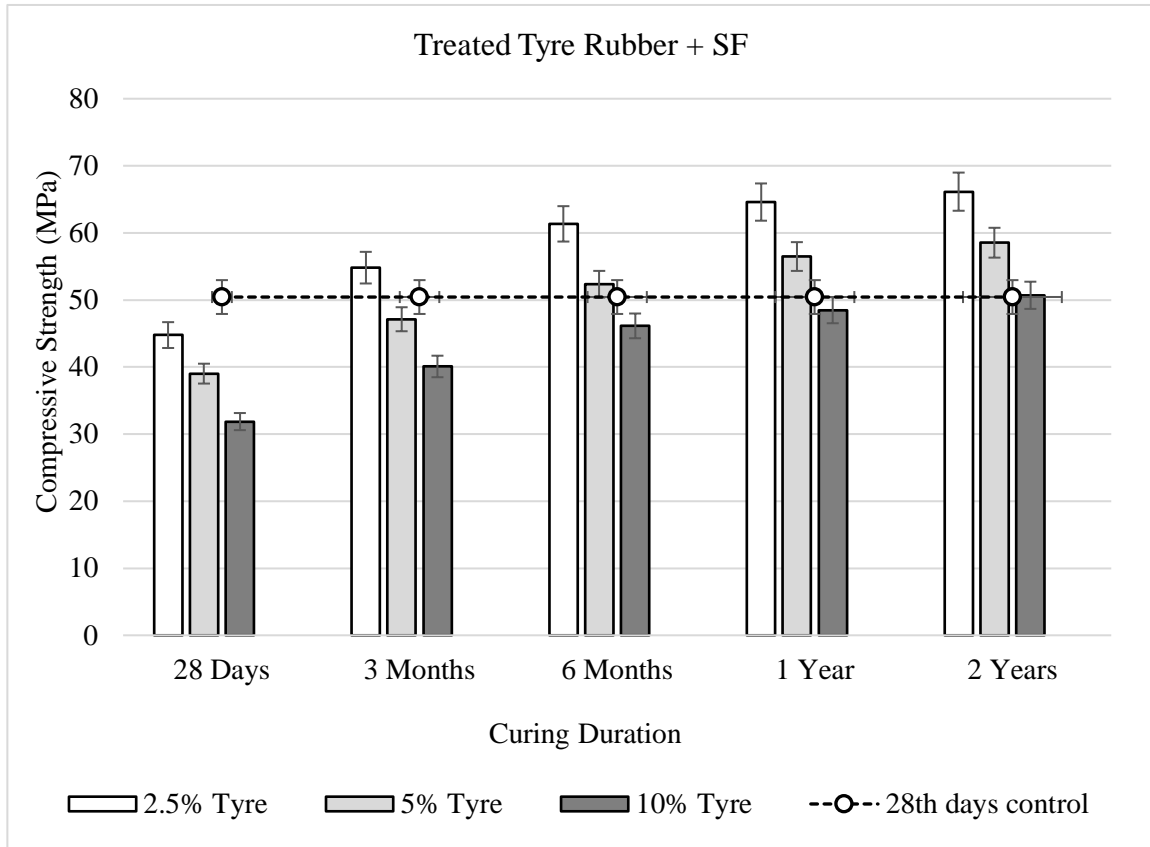


Figure 7

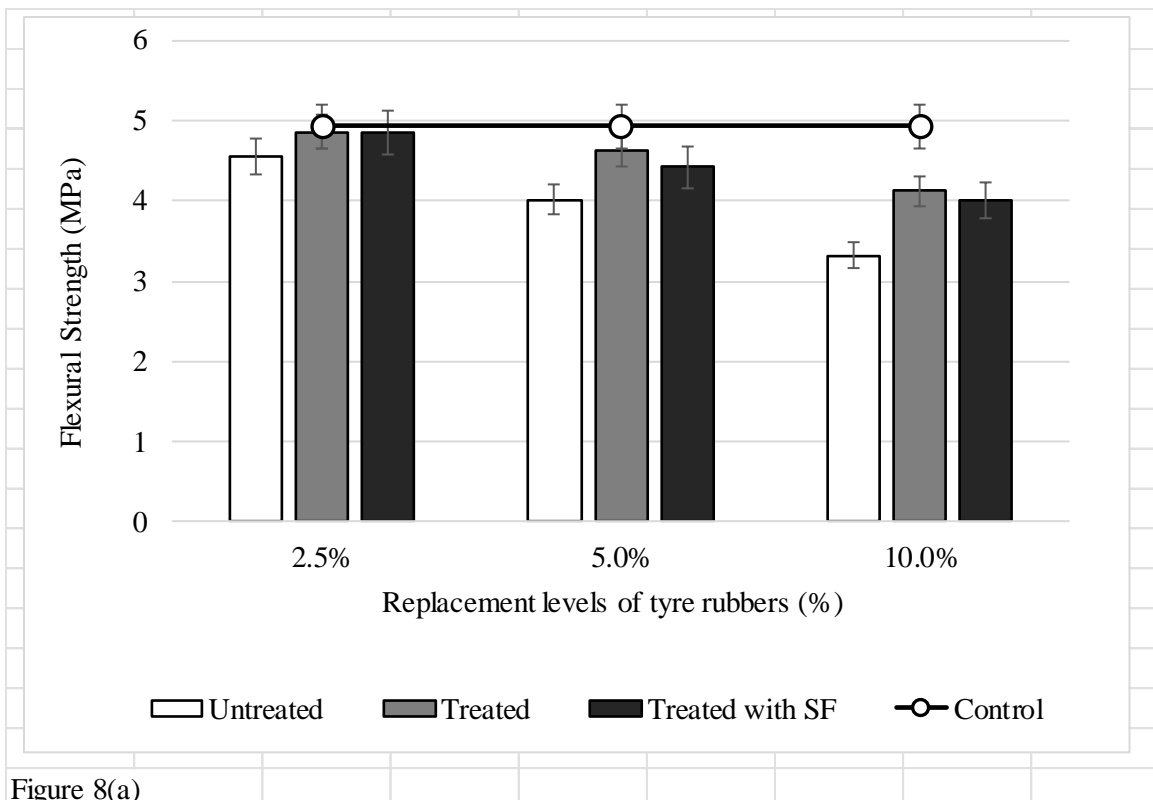


Figure 8(a)

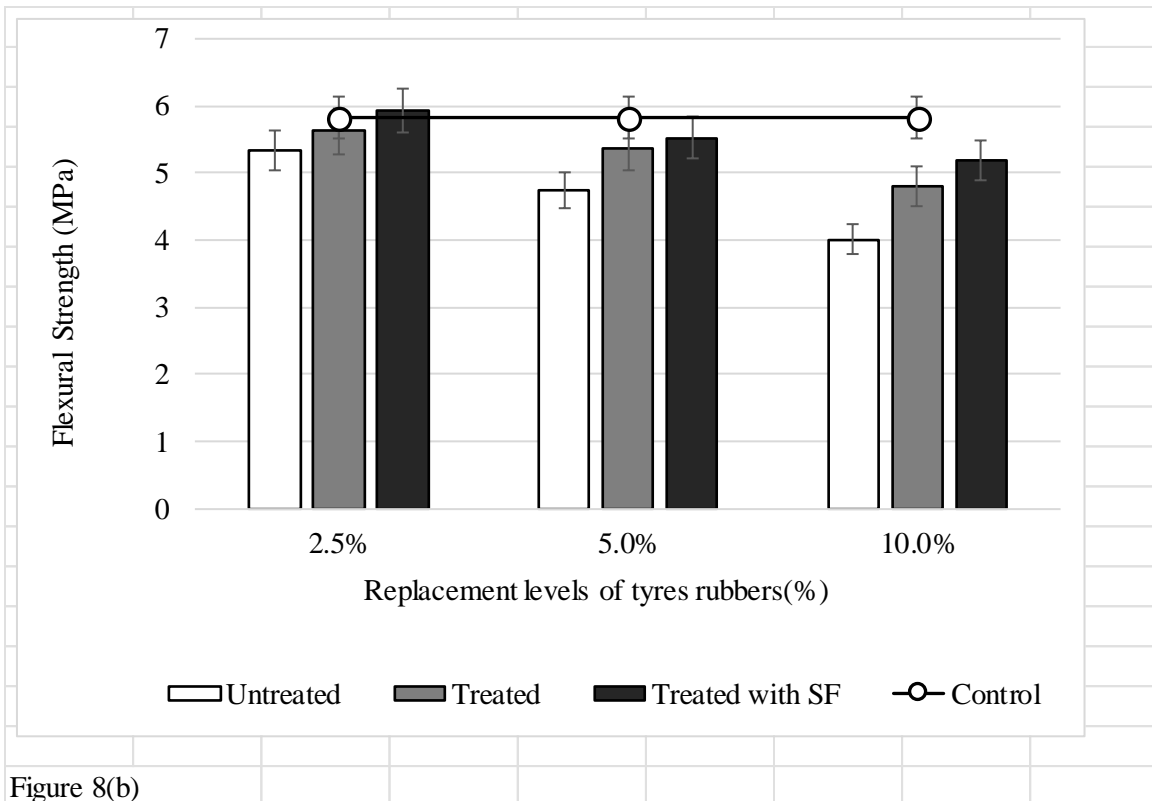


Figure 8(b)

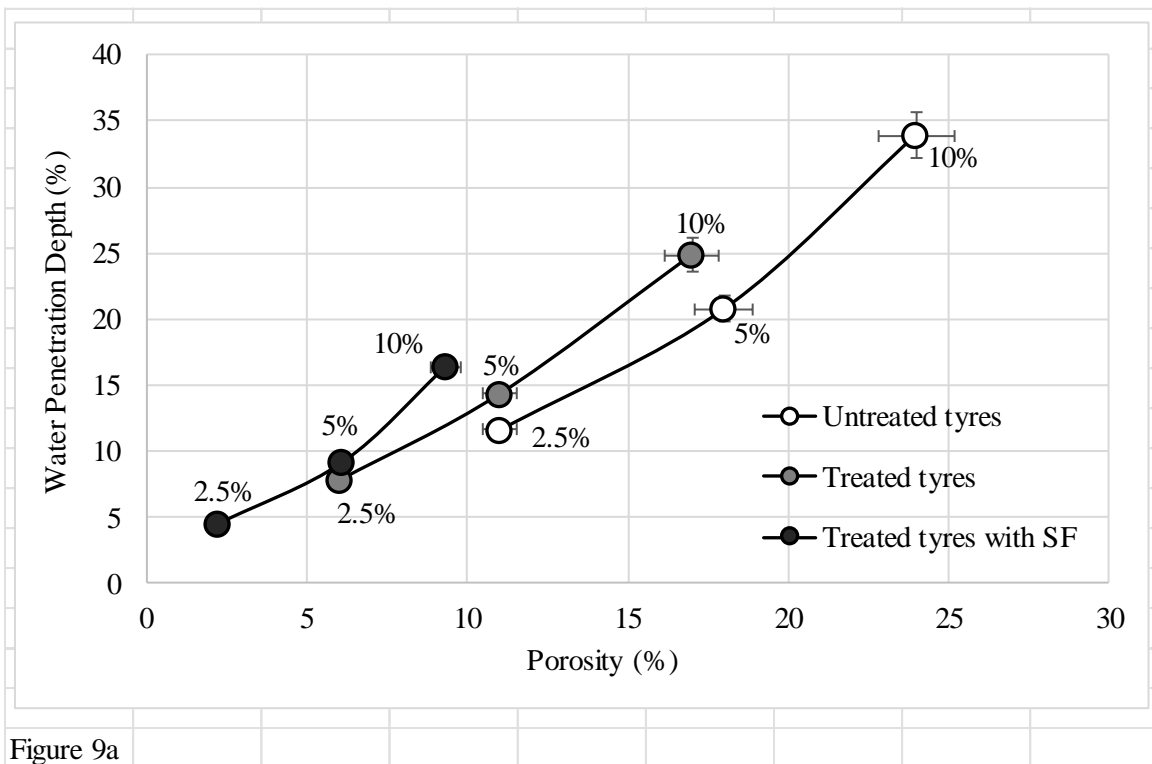


Figure 9a



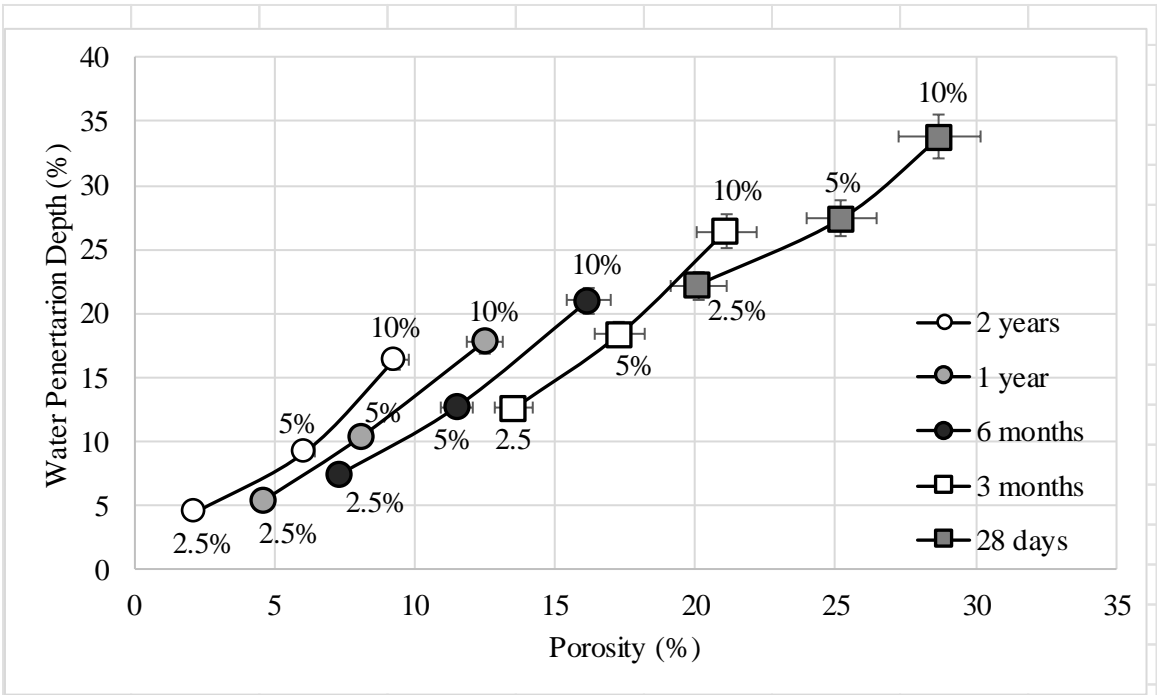


Figure 9(b)

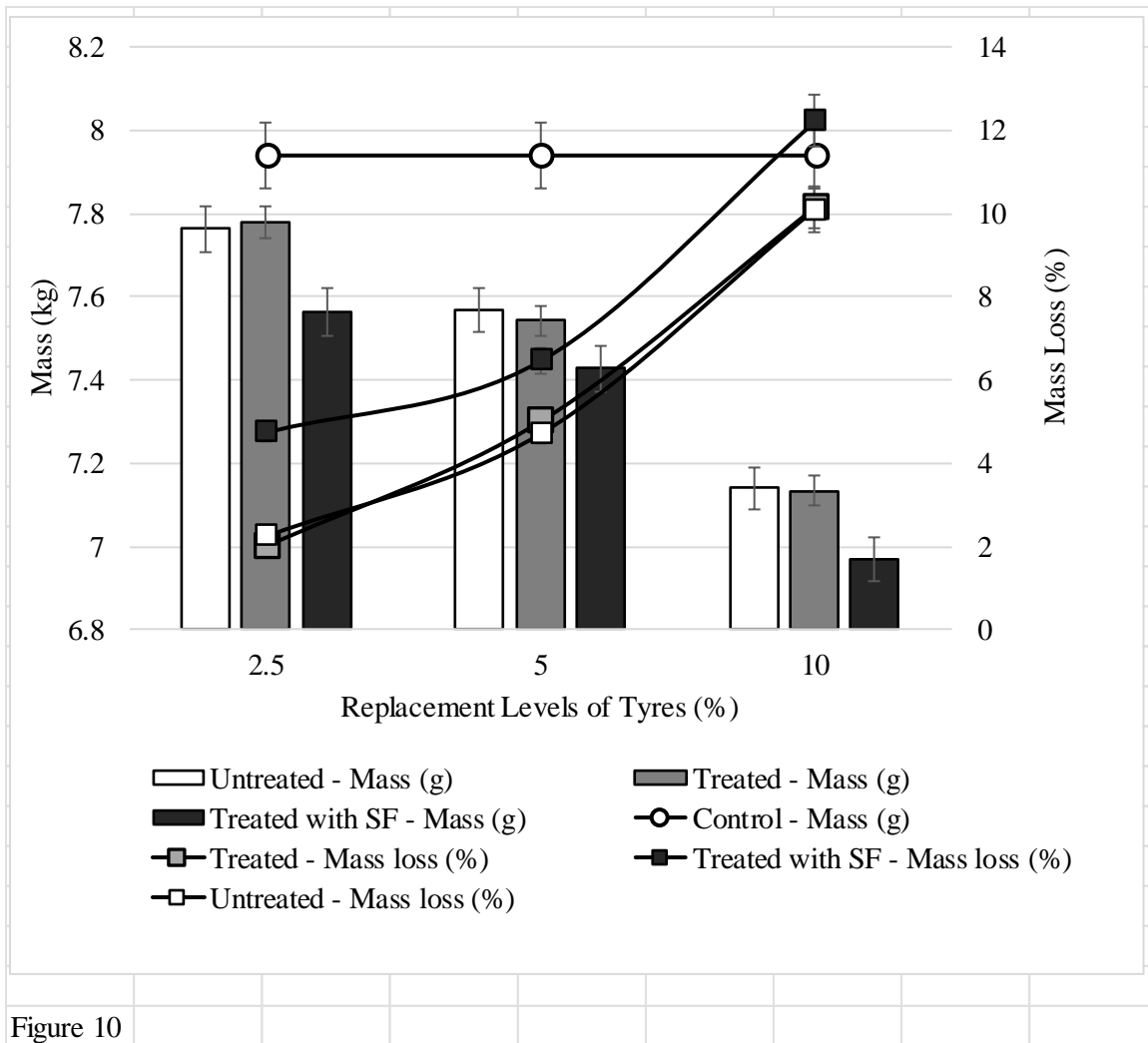


Figure 10

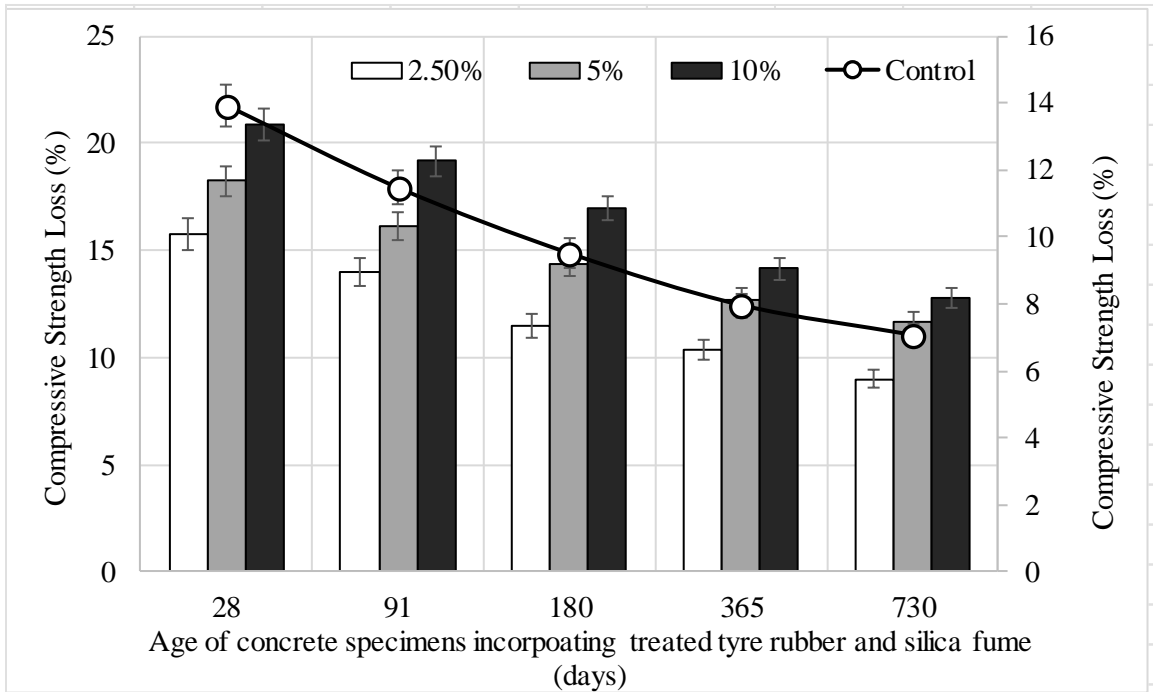


Figure 11(a)

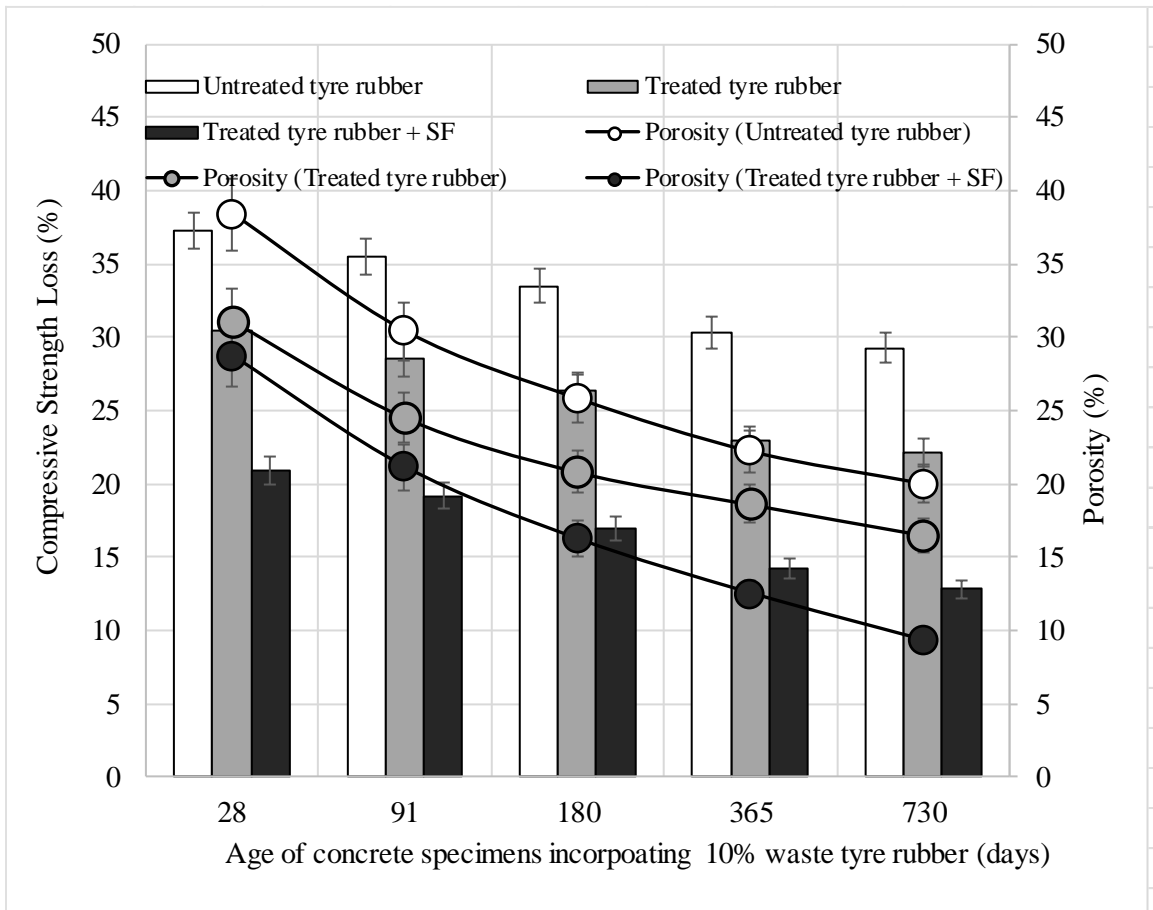


Figure 11(b)

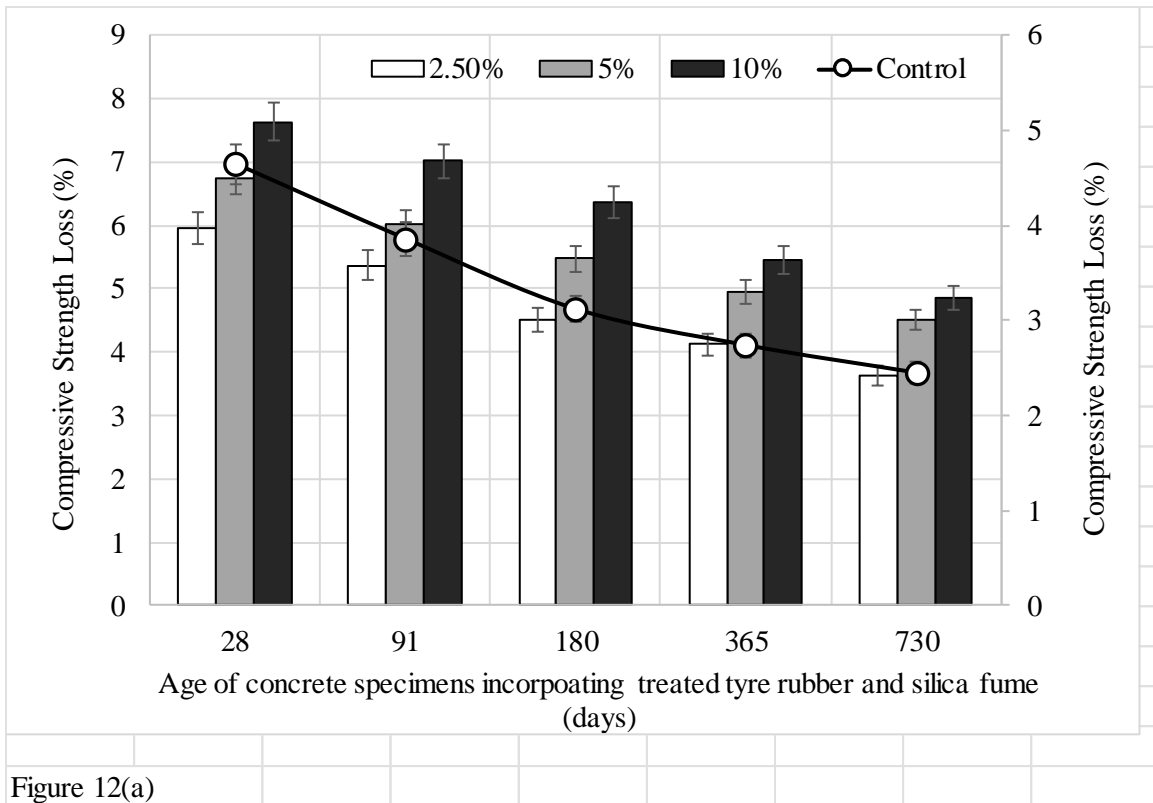


Figure 12(a)

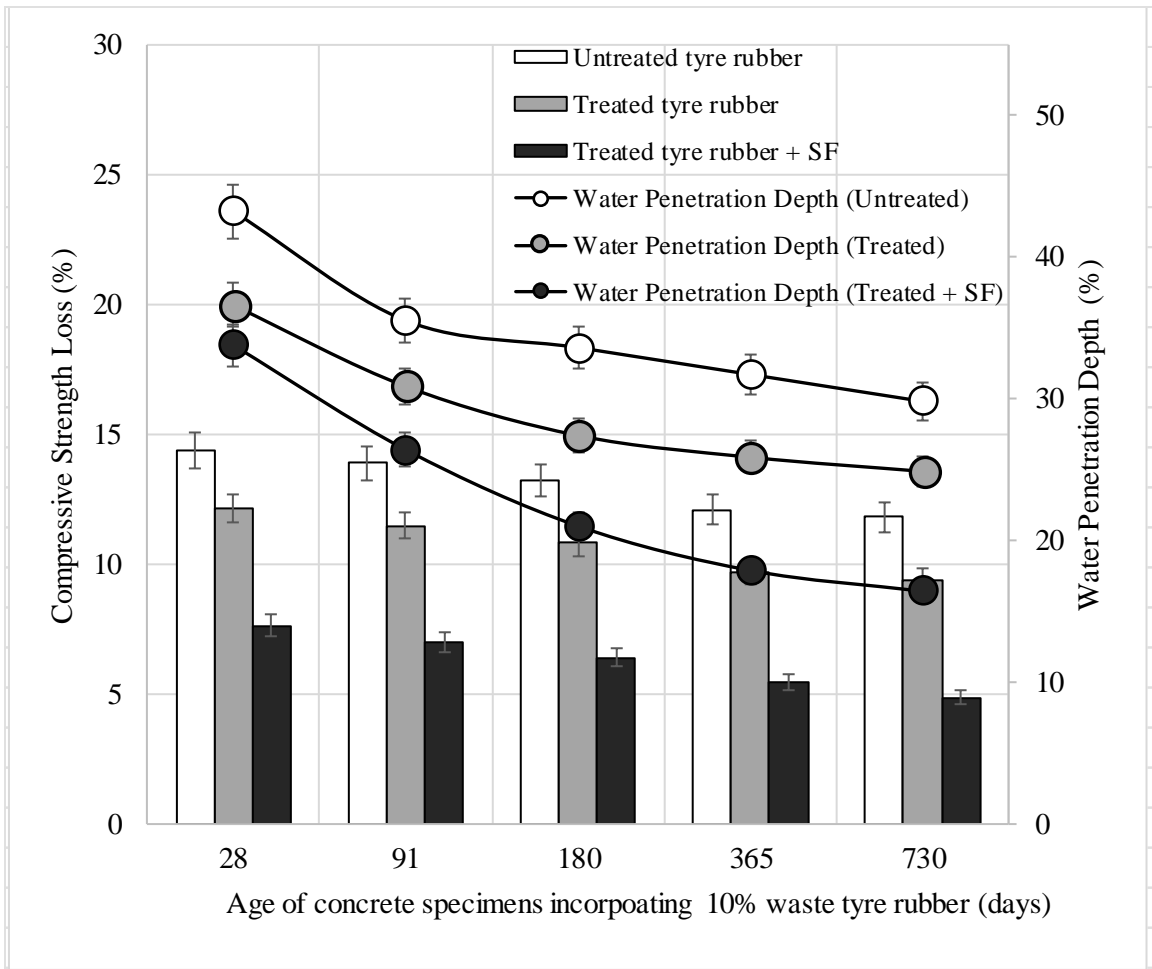


Figure 12(b)

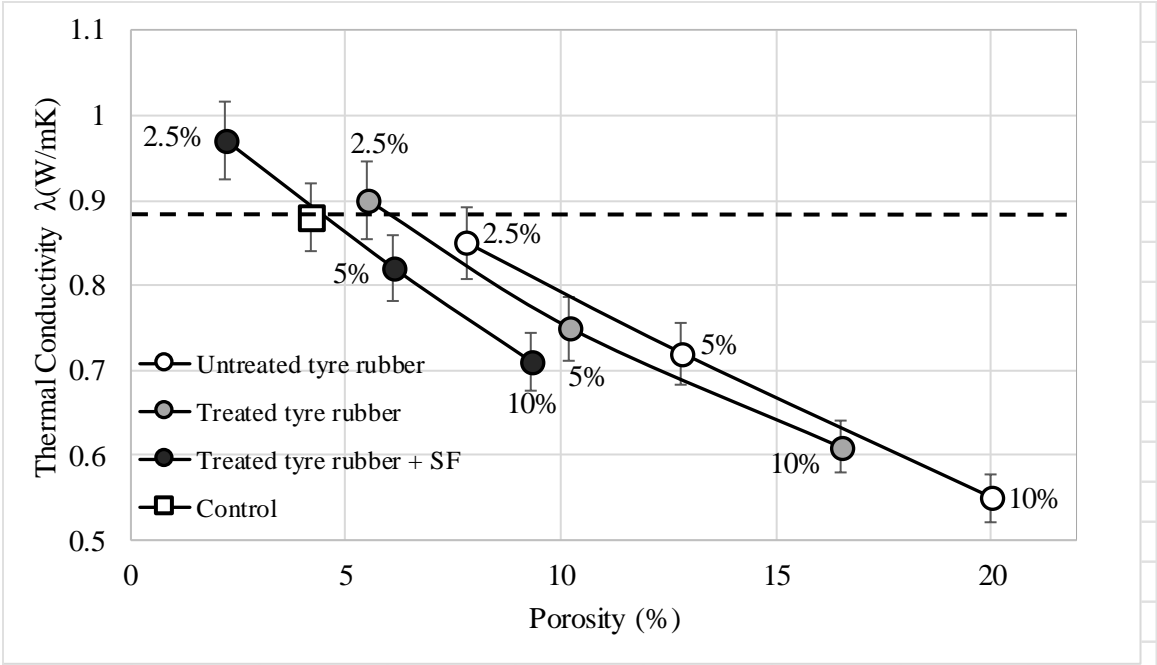


Figure 13(a)

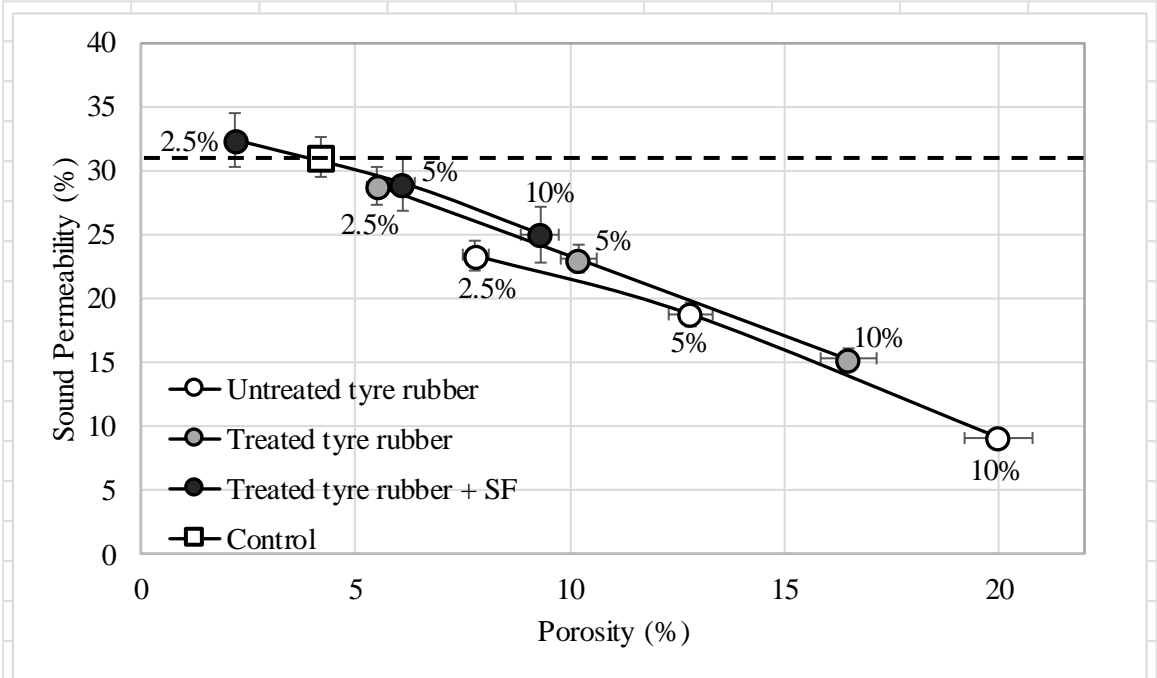


Figure 13(b)