

## Article

# Durability and Acoustic Performance of Rubberized Concrete Containing POFA as Cement Replacement

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**Abstract:** Given that rubber tires are almost immune to biological degradation, this vast amount of solid waste is a major environmental concern worldwide. Reuse of these waste tires in the construction industry is one of the strategies to minimize their environmental pollution and landfill problems, while contributing to more economical building design. Thus, we assessed the improved traits of rubberized concrete made by combining palm oil fuel ash (POFA) with tire rubber aggregates (TRAs). Studies on the effects of POFA inclusion on the durability properties of rubberized concrete with TRAs as the replacement agent for fine or coarse aggregates remain deficient. Herein, the rubberized concrete contained 20% POFA as ordinary Portland cement (OPC) substitute, and various amounts of TRAs (5, 10, 20 and 30%). The proposed mixes enclosing three types of TRAs (fiber, fine and coarse aggregates) were characterized to determine their durability and acoustic performance. The water absorption, fire endurance performance, chloride penetration, and acoustic properties of the proposed concrete were evaluated. The designed concrete showed a systematic increase in water absorption and chloride penetration with the increase in rubber amount and particle size. These POFA-modified rubberized concretes displayed a satisfactory performance up to 500 °C, and superior acoustic properties in terms of sound absorption. The presence of TRA as 30% coarse aggregate replacement was found to improve the sound absorption properties by as much as 42%.

**Keywords:** POFA; TRAs; durability; fire endurance; sound absorption



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## 1. Introduction

Over the years, with the significant increase in the number of cars worldwide, the accumulation of enormous volumes of scrap tires has become one of the major problems in environmental and waste management [1–3]. Waste tires are not naturally biodegradable under ambient conditions [4,5]. In several countries, tire rubber is being burned and used as fuel, which can result in serious ecological hazards unless carefully performed [6–9]. Used tires dumped in sanitary landfills are a significant environmental hazard and result in possible contamination [10,11]. Many recent reports have shown three interacting trends. First, there is a significant increase in the volume of scrap tires added annually to the environment [12–14]. Second, there is a considerable rise in the cost of landfill. Third, pressure from civic societies and environmental activists is constantly increasing to limit the number of available landfills, resulting in a move to ban or forbid the disposal of whole tires in landfill (in the United States, for example) [15,16]. Only small quantities of scrap tires are being used or recycled as construction materials [11,14,17]. Consequently, the

reutilization of scrap tires as rubber aggregates in concrete has become increasingly popular, thus, has generated significant research interest over the past 20 years [18–20].

Meticulous use of rubber aggregates in concrete may enhance its deformability [21] at the cost of strength reduction [22,23]. The major weakness of using rubber in concrete is the low compression strength of the rubberized concrete, that remains a problem in the use of rubberized concrete as a structural component [24]. However, for certain cases, these problems can be solved using materials that contain cementitious property instead of Portland cement [25–27]. Essentially, the application of pozzolanic materials as a partial cement replacement has multidimensional benefits in terms of technical, economical, and environmental advantages [26,28,29]. However, some pozzolanic materials are waste or by-products that often end up being disposed in landfills [30,31]. Eventually, these wastes increase as the years go by, if there are no alternative ways to reuse them [32–36]. Usually, agricultural wastes are directly disposed to landfills without any commercial return [37–39]. This practice may have adverse effects in the environment and landfills [40,41]. To reverse this situation, the present study adopted a strategy to utilize TRAs with palm oil fuel ash (POFA) to make some new types of concrete useful for structural applications. POFA has been shown to enhance the strength and durability of concrete when it replaced 20 to 30% of cement [42–45]. Additionally, reuse of various by-products from agro-industry such as POFA may minimize the hazards of disposing such materials and reduce CO<sub>2</sub> emissions associated with Portland cement manufacturing [46–48].

During the last decade, several studies have been conducted to examine the potential of plain rubberized concrete (PRC) [24,49]. Nevertheless, there are several gaps in the available information relating to the durability and fire resistance of rubberized concrete [50–54]. For example, very few studies have addressed the effects of both coarse and fine aggregate replacement on the fire resistance of this composite material. Most studies evaluated the loss of CS under elevated temperature. Hence, other properties such as weight loss and ultrasonic pulse velocity have not previously been considered. Moreover, the effects of size and types of rubber particles on durability properties, such as water absorption and chloride penetration resistance of the rubberized concrete, need further exploration. Additionally, the acoustic performance of the modified rubberized concrete needs to be evaluated in terms of sound absorption desirable for structural activities, especially in the floor component of low-cost buildings. More careful assessment is required to provide comprehensive information before rubberized concrete is widely used as a structural material in the civil engineering sector.

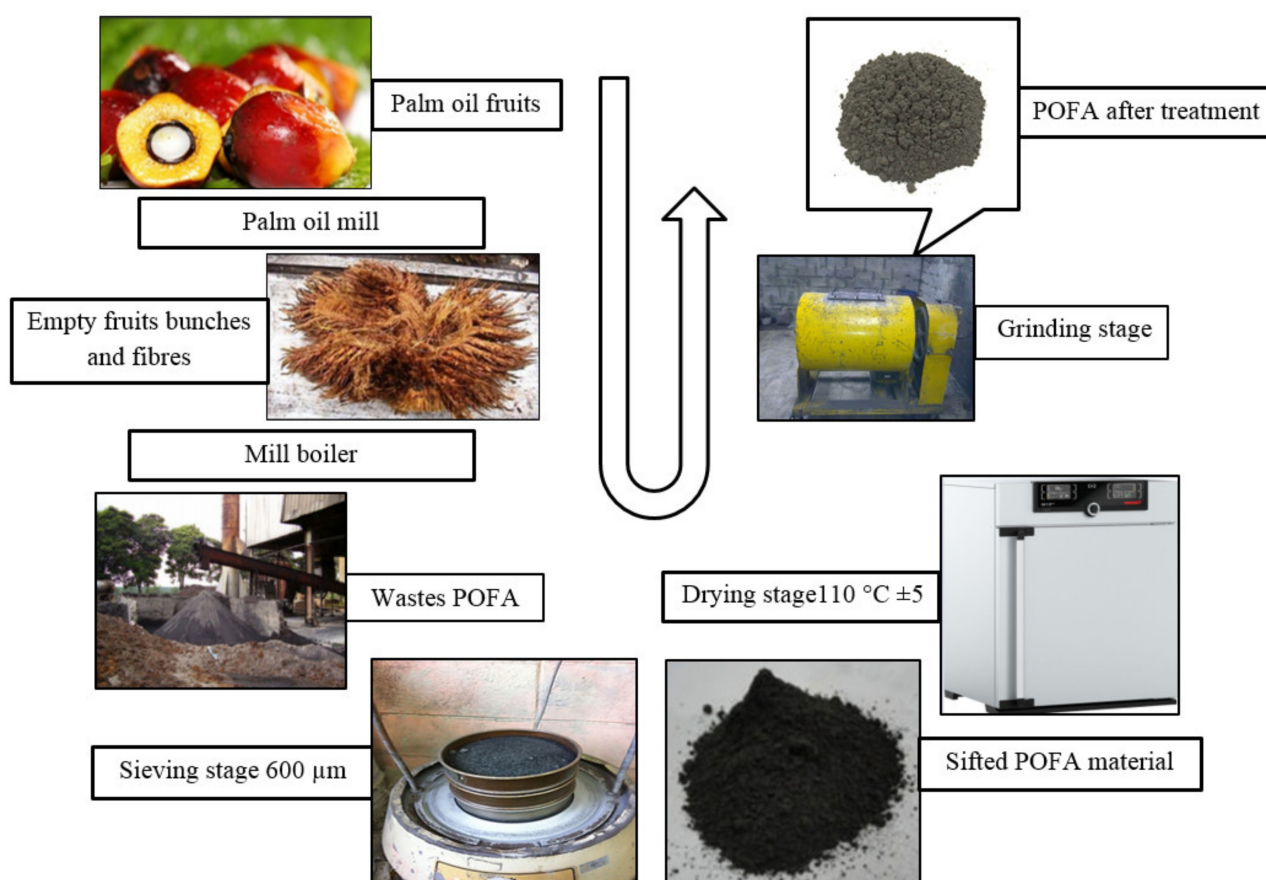
Considering the immense potential of low-cost rubberized concrete in the construction industry, some modified rubberized concrete mixes were designed by blending POFA with three kinds of TRAs. The effect of the inclusion of POFA and fiber rubber from waste tires (as a fine aggregate replacement) in rubberized concrete was assessed in terms of durability and acoustic properties. The results were compared with the POFA-modified concrete containing crumb rubber as coarse and fine aggregate replacement. The main purpose was to develop a rational mix design approach to produce modified rubberized concrete using POFA, useful for structural concrete applications. In addition, these rubberized concrete mixes with higher standards could be used in the construction of residential buildings for the provision of quiet spaces, thus, the provision of sufficient empirical knowledge is required for modeling, simulating, and supplementing the database of the existing data for this novel structural component.

## 2. Materials and Process Technology Standardization

### 2.1. Materials

In this work, Type I Ordinary Portland Cement (OPC) that met standard EN 197-1-CEM I—42.5 N was used. POFA was obtained from the burning chamber of a boiler tower in Kahang Mill (Kluang Johor, Malaysia). In order to avoid dust pollution, the ash was mixed with water before its removal from the chamber. Therefore, dehumidifying the POFA was necessary as an initial step for preparing POFA as an acceptable pozzolanic

material. As such, the ash was exposed to air for 72 h to reduce the moisture content. Then, the air-dried POFA was transferred to an oven at a temperature of  $110 \pm 5^\circ\text{C}$  for 48 h to ensure its complete dryness. After removing the ash from the oven, it was allowed to cool down in dry air to a temperature of  $27^\circ\text{C} \pm 2^\circ\text{C}$ , and the mass was determined. The ash was considered as completely dry when the difference between two successive values of mass heated for 48 h was below 0.5%. Thereafter, the oven-dried material was sieved carefully (no. 70 sieve with a mesh size of  $212\ \mu\text{m}$ ) to remove impurities and unburned materials. POFA with a particle size of less than  $200\ \mu\text{m}$  was collected and transferred to the grinding machine. A modified Los Angeles abrasion machine (5 kg nominal capacity) with 8 stainless bars each of 12 mm diameter  $\times$  800 mm length was used at 32–25 rpm to obtain ground POFA. Figure 1 shows typical agro-industrial wastes such as fresh palm oil, palm bunches, fuel burnt in generators, and ash.



**Figure 1.** Agro-industrial waste from palm oil.

It is acknowledged that the pozzolanic activity of POFA can be improved with size reduction [43]. Therefore, for best results, the POFA was ground for 6 h, wherein the crushing time duration was optimized based on the particle size analysis and strength activity index. A wet sieving process was used to check the quality of the POFA grinding process. Based on ASTM C618-05, the maximum amount of retained materials on a 45  $\mu\text{m}$  no. 325 sieve should not exceed 35%. The particle size of the POFA was lower than OPC. The percentage of materials less than  $10\ \mu\text{m}$  was observed to be 46% for POFA and 29.55% for OPC. Therefore, the obtained POFA was fine enough to improve the properties of the resultant concrete with a certain amount of POFA incorporation. Aside from addressing the environmental concerns, enhancing the properties of concrete by reutilizing POFA was one of the goals of this research, wherein POFA particle size played a vital role. Table 1 shows some essential physical and chemical characteristics of POFA and OPC.

**Table 1.** Chemical and physical specifications of used OPC and POFA.

| Materials | Chemical Combination (mass %) |                                  |                                       |                                |            |      |                  | LOI  |
|-----------|-------------------------------|----------------------------------|---------------------------------------|--------------------------------|------------|------|------------------|------|
|           | SO <sub>3</sub>               | SiO <sub>2</sub>                 | Al <sub>2</sub> O <sub>3</sub>        | Fe <sub>2</sub> O <sub>3</sub> | CaO        | MgO  | K <sub>2</sub> O |      |
| OPC       | 4.39                          | 16.40                            | 4.24                                  | 3.53                           | 66.85      | 2.39 | 0.22             | 1.67 |
| POFA      | 1.59                          | 63.70                            | 3.68                                  | 6.27                           | 5.97       | 4.11 | 9.15             | 4.46 |
|           | Physical properties           |                                  |                                       |                                |            |      |                  |      |
|           | Specific gravity              | Particle retained on 45 µm sieve | Specific surface (cm <sup>2</sup> /g) | Strength Activity Index (%)    |            |      |                  |      |
|           |                               |                                  |                                       | At 7 days                      | At 28 days |      |                  |      |
| OPC       | 3.15                          | 4.58%                            | 5137.11                               | -                              | 98.6       |      |                  |      |
| POFA      | 2.43                          | 0.73%                            | 7796.17                               | -                              | 103.4      |      |                  |      |

Figure 2 shows the transmission electron microscopy (TEM) image of ground POFA, indicating the particles' morphology. The ash was ground for 6 h to reduce the median particle size to below 10 µm. The shape of the POFA particles was spherical, exhibiting some clustering.

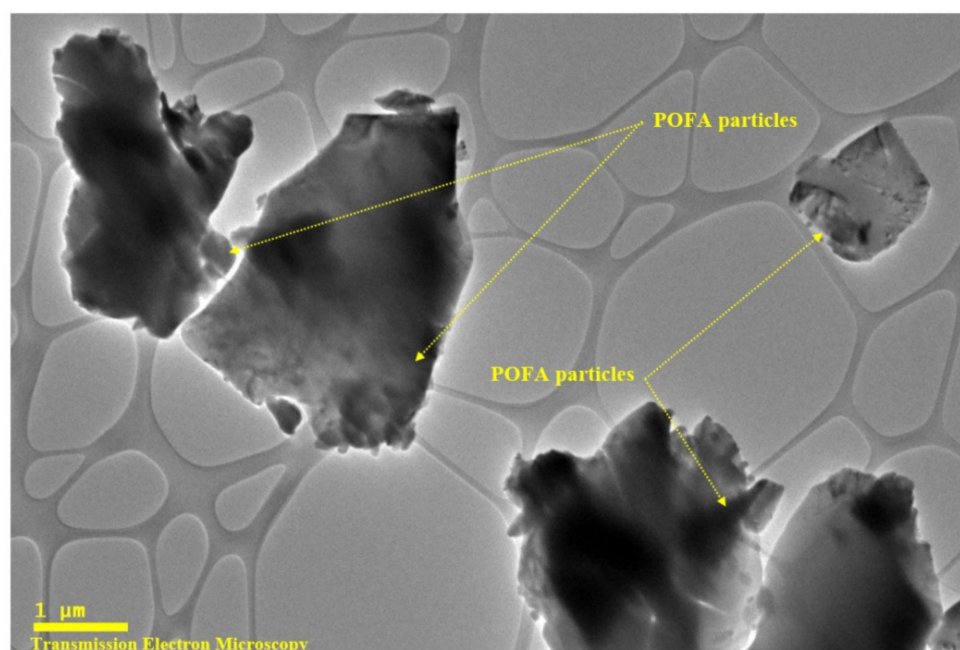
**Figure 2.** TEM image of POFA.

Figure 3 displays the XRD profiles of POFA. The major mineral was crystalline quartz that showed an intense Bragg's peak at 27.9 degrees. Furthermore, the POFA contained opal resulting from the calcination of the organic constituents of palm oil fibers and shells.

Crushed granite stone and river sand were used as the natural aggregates. The crushed stone was free from deleterious materials, such as organic matter, grass and leaves, dry mud, silt, and oil. The natural aggregates were kept under SSD conditions to ensure that they would not affect the amount of free water in the mix design, in accordance with ASTM C33 [55] requirements. Sieve analysis was conducted to determine the grading of fine and coarse aggregate according to ASTM C136. Meanwhile, three types of TRAs were used in this study (Figure 4). The tire chips exhibited differences in shape and particle size and were, thus, classified into three types of rubber aggregates. Fine fiber tire rubber aggregate—Type R1—had a maximum length of 16 mm. Fiber rubber aggregate (R<sub>1</sub>) partially replaced the natural fine aggregate. Fine granular tire rubber aggregate—Type R2 (sized

1 to 4 mm)—partially replaced the fine aggregate. Coarse granular tire rubber aggregate—Type R3 (particle size 5 to 8 mm)—partially replaced conventional coarse aggregate.

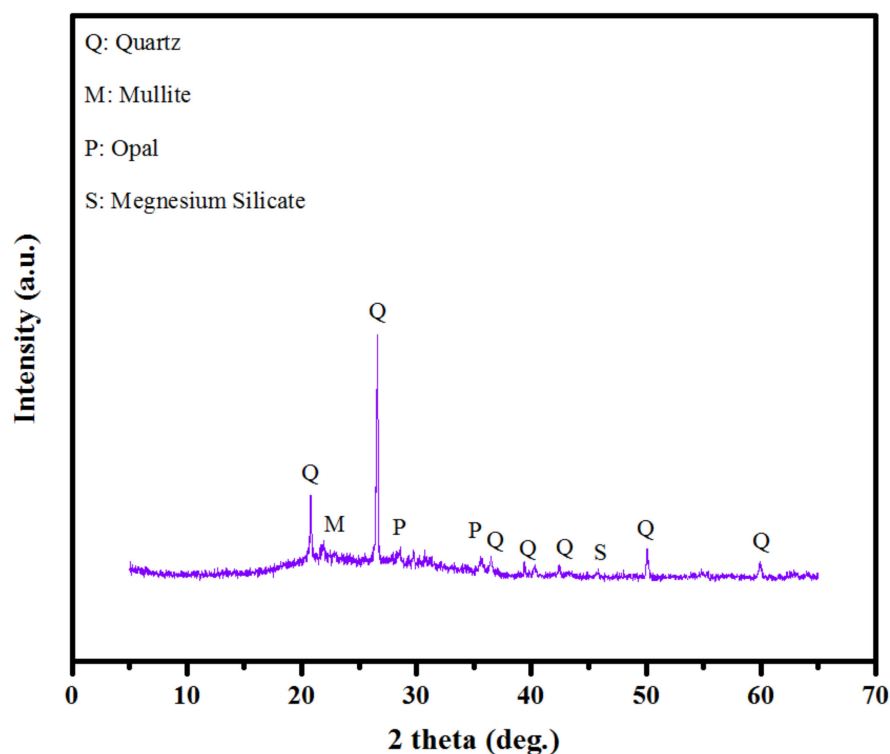


Figure 3. XRD patterns of ground POFA.

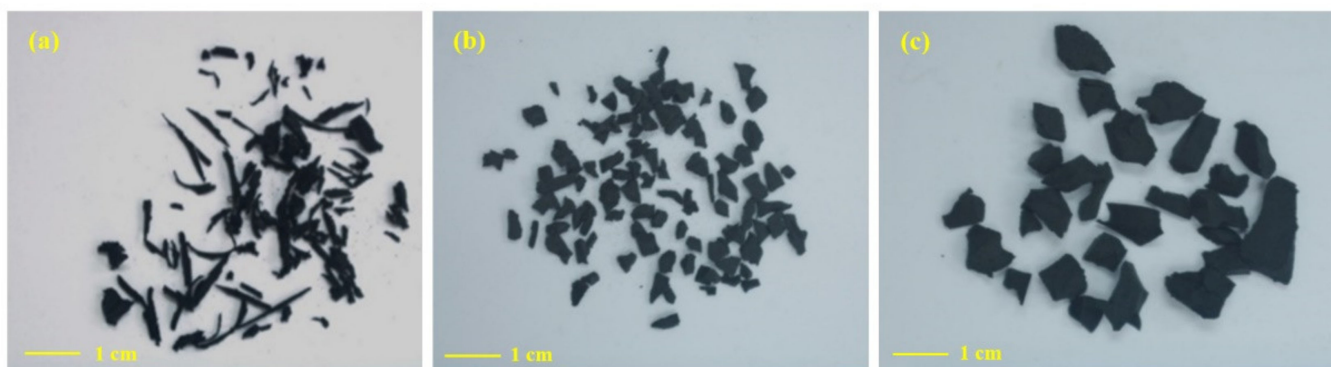


Figure 4. (a) Fine fiber rubber aggregate—Type R1. (b) Fine granular rubber aggregate—Type R2. (c) Coarse granular rubber aggregate—Type R3.

Figure 5 shows the limitation of grading area where the TRAs replaced the natural aggregates. Rubber aggregate types R<sub>1</sub> and R<sub>2</sub> partially replaced the fine aggregate in the proposed concrete mix. Meanwhile, rubber aggregate type R3 partially replaced the coarse aggregate. The substitution was based on the grading of TRAs, avoiding the extra pores and consequently reducing the CS of the resulting concrete.

A synthetic polymer-based super-plasticizer (SP) was used to reduce the water demand, thus, achieving the desired workability. The used SP was in compliance with ASTM C494-2010 requirements for types A and F. Generally, this type of SP is dispensed at a rate of 0.8 to 3 L per 100 kg of cementitious material. Table 2 illustrates the characteristics of the used SP.

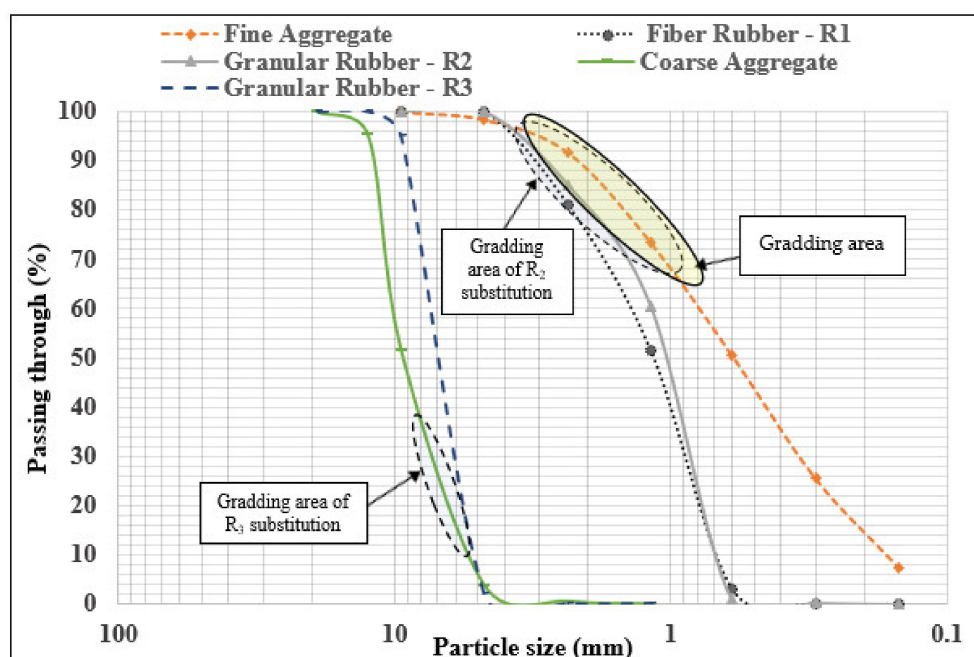


Figure 5. Sieve analysis of TRAs and natural aggregate.

Table 2. Specifications of the used SP.

|                  |                                                    |
|------------------|----------------------------------------------------|
| Specific Gravity | 1.210 at 25 °C                                     |
| Color            | Dark-brown liquid                                  |
| Chloride Content | Chloride-free to BS 5075: Part 1 and 3             |
| Air Entrainment  | Maximum 1%                                         |
| Freezing Point   | 0 °C—can be reconstituted if stirred after thawing |

## 2.2. Rubberized Concrete Mix Design

POFA was utilized as the pozzolanic material and partially replaced OPC to improve the mechanical properties (especially the CS) of concrete. An amount of 20% of OPC was replaced by POFA and the water–binder ratio was 0.38 with an SP of 1% to satisfy the desired workability from the previous steps of mix design modification. To establish the maximum amount of TRA that could be replaced as fine or coarse aggregate so that the produced concrete could be considered as a structural application, several trials of mix design were conducted with different types of TRA. The mix proportion design was established based on the volume method as described in ACI 211.1. Table 3 displays the mix proportion of the developed POFA-modified rubberized concrete.

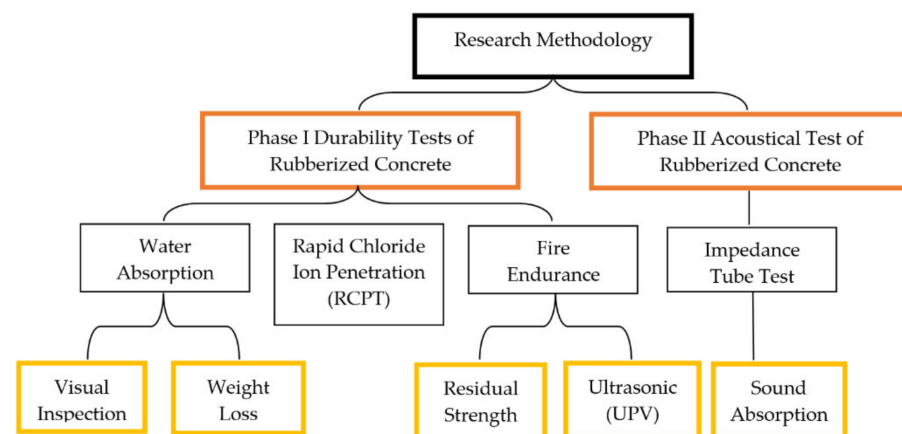
## 2.3. Tests Program

As shown in Figure 6, Phase I dealt with the durability assessment of the rubberized concrete, namely: Step 1 evaluated the porosity of rubberized concrete and its water absorption in accordance with existing standards; Step 2 assessed the resistance against chloride exposure; and Step 3 assessed the fire performance of the rubberized concrete. Phase II dealt with the assessment of the acoustic properties of the rubberized concrete, namely: Step 1 prepared various specimens with proper dimensions according to the existing methods of the testing procedure; and Step 2 evaluated the sound absorption properties of the rubberized concrete using the impedance tube test.

**Table 3.** The mix proportion of POFA-modified rubberized concrete.

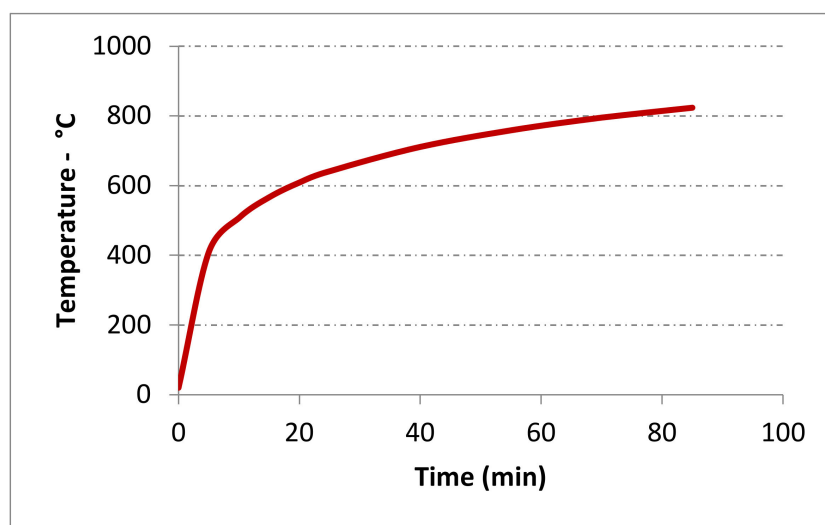
| Mixes     | Binder                   |                           | Waste Tire Aggregates                  |                                  |                                    | Natural Aggregates              |                                    |
|-----------|--------------------------|---------------------------|----------------------------------------|----------------------------------|------------------------------------|---------------------------------|------------------------------------|
|           | OPC (kg/m <sup>3</sup> ) | POFA (kg/m <sup>3</sup> ) | Fine Fiber Rubber (kg/m <sup>3</sup> ) | Fine Rubber (kg/m <sup>3</sup> ) | Coarse Rubber (kg/m <sup>3</sup> ) | River Sand (kg/m <sup>3</sup> ) | Crushed Stone (kg/m <sup>3</sup> ) |
| CP        | 450                      | 0                         | 0                                      | 0                                | 0                                  | 782                             | 874.5                              |
| CP20      | 405                      | 135                       | 0                                      | 0                                | 0                                  | 782                             | 874.5                              |
| R1 5CP20  | 405                      | 135                       | 13.17                                  | 0                                | 0                                  | 742.8                           | 874.5                              |
| R1 10CP20 | 405                      | 135                       | 26.35                                  | 0                                | 0                                  | 703.6                           | 874.5                              |
| R1 20CP20 | 405                      | 135                       | 52.68                                  | 0                                | 0                                  | 625.25                          | 874.5                              |
| R1 30CP20 | 405                      | 135                       | 79                                     | 0                                | 0                                  | 546.9                           | 874.5                              |
| R2 5CP20  | 405                      | 135                       | 0                                      | 19.85                            | 0                                  | 742.8                           | 874.5                              |
| R2 10CP20 | 405                      | 135                       | 0                                      | 39.7                             | 0                                  | 703.6                           | 874.5                              |
| R2 20CP20 | 405                      | 135                       | 0                                      | 79.4                             | 0                                  | 625.25                          | 874.5                              |
| R2 30CP20 | 405                      | 135                       | 0                                      | 119.1                            | 0                                  | 546.9                           | 874.5                              |
| R3 5CP20  | 405                      | 135                       | 0                                      | 0                                | 22.23                              | 782                             | 830.77                             |
| R3 10CP20 | 405                      | 135                       | 0                                      | 0                                | 44.46                              | 782                             | 787.1                              |
| R3 20CP20 | 405                      | 135                       | 0                                      | 0                                | 88.93                              | 782                             | 699.6                              |
| R3 30CP20 | 405                      | 135                       | 0                                      | 0                                | 133.92                             | 782                             | 612.1                              |

CP control mix, CP20 cement (OPC) replaced by 20% POFA, R1 5–30 (fine fiber rubber aggregate replacement), R2 5–30 (fine granular rubber aggregate replacement), R3 5–30 (coarse rubber granular aggregate replacement).

**Figure 6.** Schematic representation of the test program.

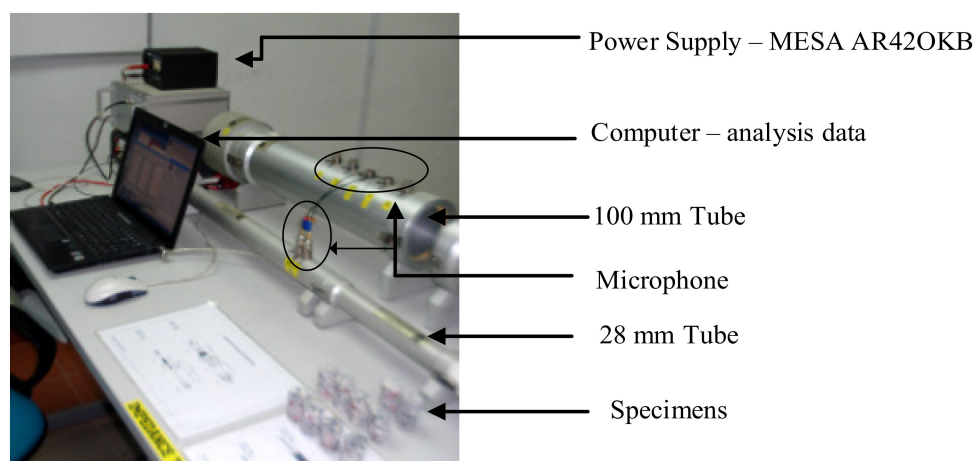
The durability test determined the effects of elevated temperature and rubber particle size and shape, on the chloride penetration and water absorption of the rubberized concrete. The water absorption and rapid chloride penetration test (RCPT) were conducted based on ASTM C1202 and ASTM C642 protocols, respectively. The objective of the fire test was to explain the behavior of the rubberized concrete on exposure to high temperature. Different types and amounts of rubber particles were used for the comprehensive evaluation of the post-fire properties of the rubberized concrete. The rate of heat development in the furnace was compared with a standard rating recommended by ISO 834 (ISO, 2012). An automatic electric furnace (Carbolite Furnace 1100) was used to simulate the fire situation at various temperatures ( $27 \pm 2$  °C to 150 °C, 300 °C, 500 °C, and 800 °C) up to a maximum of 1200 °C. This range of elevated temperature was suggested and applied by Al-Mutairi et al. (2010) for the evaluation of rubberized concrete performance. The specimens were kept at the designed temperature for one hour to simulate an actual fire situation. The specimen at ambient temperature ( $27 \pm 2$  °C) was used as the control, and tested to compare the post-fire properties of the rubberized concrete. Figure 7 shows the temperature against time

curve. The loss of CS, loss of weight, and UPV were determined to evaluate the post-fire properties of POFA-included rubberized concrete.



**Figure 7.** Experimental temperature–time curve of the rubberized concrete.

As shown in Figure 8, the two-microphone transfer-function (impedance tube) method was used in accordance with the ASTM E1050-10 standard to measure the impedance and absorption of the acoustic concrete. The absorption coefficient and acoustic impedance of sound absorbance by the materials (circular-cut in small samples) were measured in the range of 100 to 6000 Hz. The improvement of the acoustical properties of the modified rubberized concrete was carried out using “Acoustic Material Properties Measurement System SCS9020B—Kundt/T60/TL Tubes” as a complete set of hardware and software tools. The acoustic property, sound absorption coefficient ( $\alpha$ ), was recorded. The “SCS 8100” software was utilized to record the data. In this study, the rubberized concrete was exposed to low frequencies from 100 to 1000 Hz, and high frequencies from 1000 to 5000 Hz, to evaluate the effect of different sizes and levels of tire aggregates in concrete. Moreover, sound absorption can be represented as a single value, this value can be described as the noise reduction coefficient (NRC). The noise reduction coefficient expresses the scale of the amount of sound energy absorbed by the material surface. The noise reduction coefficient ranges from 0 (total reflection) to 1.00 (total absorption). The noise reduction coefficient was calculated as the average of the sound absorption at frequencies of 250, 500, 1000 and 2000 Hz. The noise reduction coefficient (NRC) was estimated via:



**Figure 8.** Impedance tube instrument.

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \quad (1)$$

where NRC is the noise reduction coefficient, and  $\alpha_{250}$ ,  $\alpha_{500}$ ,  $\alpha_{1000}$  and  $\alpha_{2000}$  are the sound absorption coefficients at 250, 500, 1000 and 2000 Hz, respectively.

### 3. Results and Discussion

#### 3.1. Water Absorption

Figure 9 illustrates the water absorption of the various modified rubberized concretes at 28 and 90 days. The water absorption values were 3.43 and 3.35% at 28 days, and 3.21% and 3.02% at 90 days, for plain and 20% POFA replacement, respectively. The water absorption of the rubberized concrete containing type R<sub>1</sub> concrete varied from 4.22% to 7.21% at 28 days, and from 3.9% to 7.03% at 90 days, depending on the fine fiber rubber content. The water absorption behavior of the concrete was affected by the level of rubber replacement, and increased with the increase in rubber content. Similarly, the absorption behavior of R<sub>2</sub> rubberized concrete was in the range of 4.15% to 6.8%, and 3.82% to 6.6%, at 28 and 90 days, respectively. The lowest level of water absorption was obtained in concrete with 5% rubber replacement, which was 4.15% and 3.82% at 28 and 90 days, respectively. The highest level of porosity was obtained for the concrete R<sub>2</sub> 30CP20 with percentages of 6.8% and 6.6%, at 28 and 90 days, respectively. A similar trend was observed for concrete incorporated with R<sub>3</sub> aggregates where the water absorption was in the range of 4.4% to 7.9%, and 4.08% to 7.72%, at 28 and 90 days, respectively. In general, the presence of coarse rubber aggregate (R<sub>3</sub>) increased the water absorption of the designed concrete because of the weak cement-paste-rubber-aggregate interactions. Ganjian et al. [53] reported that the water absorption of rubberized concrete can increase with the increase in particle size and amount of rubber aggregate. Furthermore, the water absorption of R<sub>1</sub> concrete was slightly higher than that of R<sub>2</sub> concrete, possibly because of a deviation of rubber particle size owing to the sand grain size distribution and an increase in the amount of air trapped during mixing procedures. Therefore, the results demonstrated that the water absorption of the rubberized concrete was higher than that of normal concrete. Moreover, the particle size of rubber, level of concentration, and type of rubber aggregates affected the level of water absorption. Coarser rubber particles were found to increase water absorption, compared with fine particles. Meanwhile, among fine rubber aggregates, the fine granular ones showed lower absorption than the fine fiber rubber aggregates.

#### 3.2. Rapid Chloride Penetration Test (RCPT)

Figure 10 presents the results of rapid chloride ion penetration in terms of the electric charge passed in coulombs through the respective types of modified rubberized concrete. Similar to water absorption, the lowest values of rapid chloride penetration were obtained at 90 days for all the studied concrete specimens. The total charge values that passed through the control specimens (CP) were 2092 and 1791 c at 28 and 90 days, respectively, classifying it as moderate and low levels of chloride permeability, respectively. Moreover, an average of 14.3% reduction was observed within the extension of the curing period at 90 days. This classification was consistent with the ASTM C1202, which states that chloride ion penetrability based on charges passed is considered as: high, for values greater than 4000 c; moderate, for values between 2000 and 4000 c; low, for values between 1000 and 2000 c; and very low, for values between 100 and 1000 c.

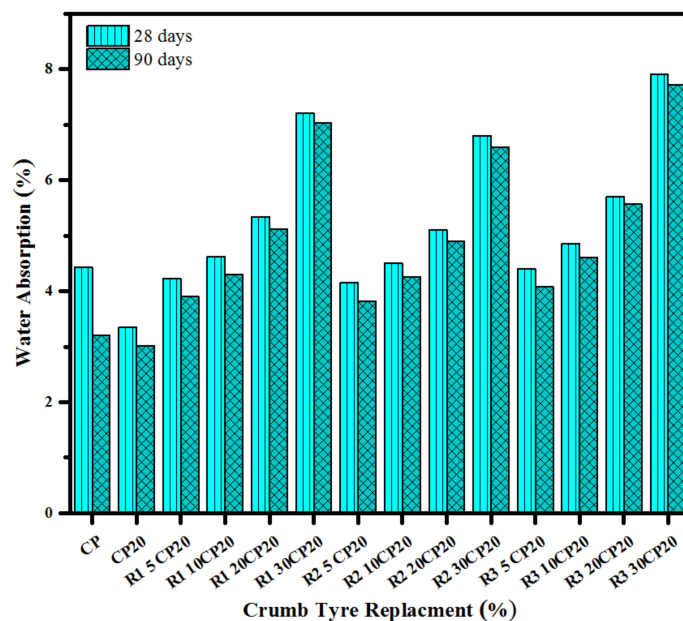
Figure 10 displays the impact of adding 20% POFA on the rate of reduction in chloride penetration. The rate of coulombs charge passed was reduced to 1956 and 1506 c at 28 and 90 days, respectively. Inclusion of 20% POFA was shown to improve the performance in terms of increased resistance to chloride penetration, compared with normal concrete. The rate of increase in the reduction in chloride penetration was 23%. The permeability resistance of POFA concrete was improved because of the pore refinement within the concrete micro-structure induced by POFA, or the transformation of large permeable pores

into smaller ones [56]. The results of the permeability by chloride ion penetration for R<sub>1</sub> rubberized concrete were in the range of 2165 to 3128 c at 28 days, and 1720 to 2757 c at 90 days. It was observed that chloride ion penetration could systematically increase with the increase in concentration of R<sub>1</sub> rubber aggregates. The same trend was observed for R<sub>2</sub> rubberized concrete wherein the chloride ion penetration increased from 2122 to 2916 c, and from 1640 to 2584 c, at 28 and 90 days, respectively. Moreover, type R<sub>2</sub> rubberized concrete showed lower chloride ion penetration, compared with type R<sub>1</sub> rubberized concrete in which air was easily trapped by the rough surface of the tire particles [44]. The progressive increase in chloride ion penetration with increasing rubber content may be attributed to the weak bonding between rubber particles and cement paste [57]. These results are supported by Ganjean et al. [53] and Gesoglu and Guneyisi [54], who acknowledged an increase in permeability at higher concentrations of rubber particles. The chloride ion penetration of concrete containing R<sub>3</sub> particles was the highest among all types of rubberized concrete, irrespective of the rubber content. However, this was more pronounced in concrete made with 20% and 30% R<sub>3</sub> rubber content. In summary, type R<sub>1</sub> rubberized concrete showed the best performance in the chloride ion penetration test. Despite the fact that coarser rubber particles yielded increased permeability, the obtained result showed that all types of rubberized concrete were classified at the low to moderate level of permeability according to ASTM C 1202, C2012.

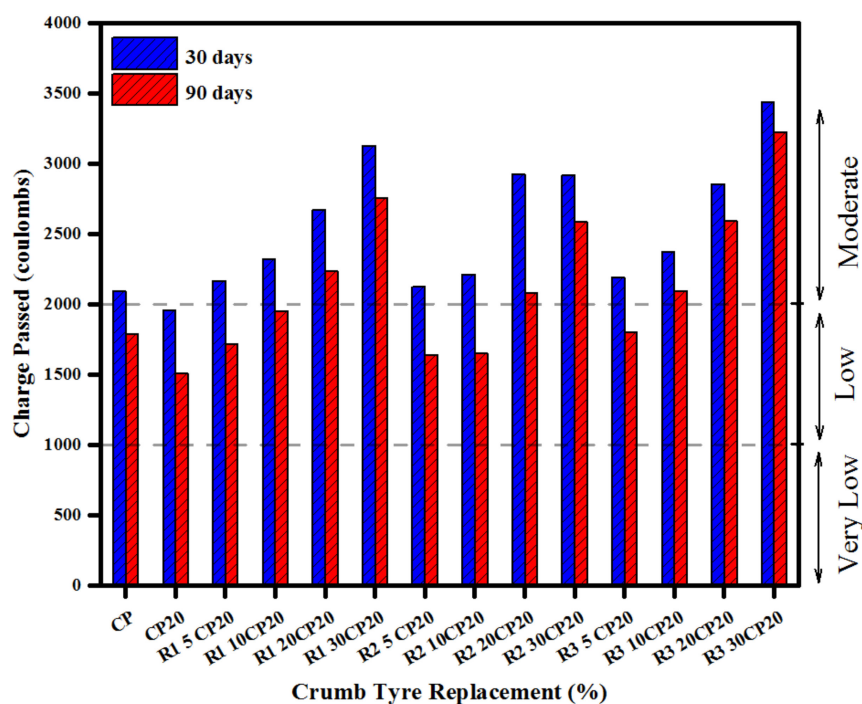
### 3.3. Fire Endurance

#### 3.3.1. Effect of Temperature on Physical Properties of Concrete Containing Type R1 Rubber Aggregates

The resistance and stability of structures during a fire is the most important criteria in the safety of buildings. Compared with wood and steel structures, concrete generally exhibits good capability for sustaining resistance and stability under fire exposure. Naturally, concrete is incombustible and does not emit gas or toxic smoke and fumes when exposed to fire. Although concrete can retain sufficient strength at high temperatures, it deteriorates when subjected to intensive temperatures in the range of 100 °C to 800 °C for a long time. Thus, the durability of concrete structures at high temperatures reduces the risk of structural collapse [58,59]. To validate this claim, we evaluated the effect of elevated temperature on the proposed novel concrete containing TRAs.

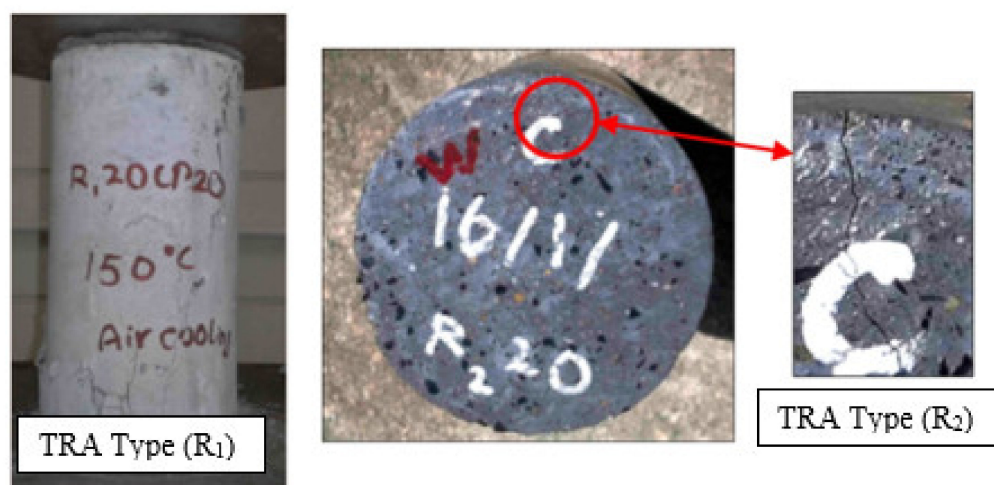


**Figure 9.** Effect of POFA and different types and levels of TRAs on water absorption values of concrete at 28 and 90 days.



**Figure 10.** Effect of POFA and different types and concentrations of TRAs on resistance to chloride-ion penetration in concrete at 30 and 90 days.

The changes in the physical properties of the modified rubberized concrete were attributed to the exposure to high temperatures that did not require any test. A visual inspection of the surface texture, color, and shape of the concrete specimens was made to evaluate the effect of elevated temperature on the rubberized concrete. Notably, these data and properties may not exhibit the actual or reliable structural information about the aforementioned concrete, but may demonstrate the necessary information for its failure tendency. Figure 11 shows an insignificant change in the surface color at temperatures of 150 °C and 300 °C. Before heating, all specimens were in perfect condition with a smooth surface and perfect edges.



**Figure 11.** Hair cracks on the R2 specimen's surface due to water cooling after exposure to 150 °C.

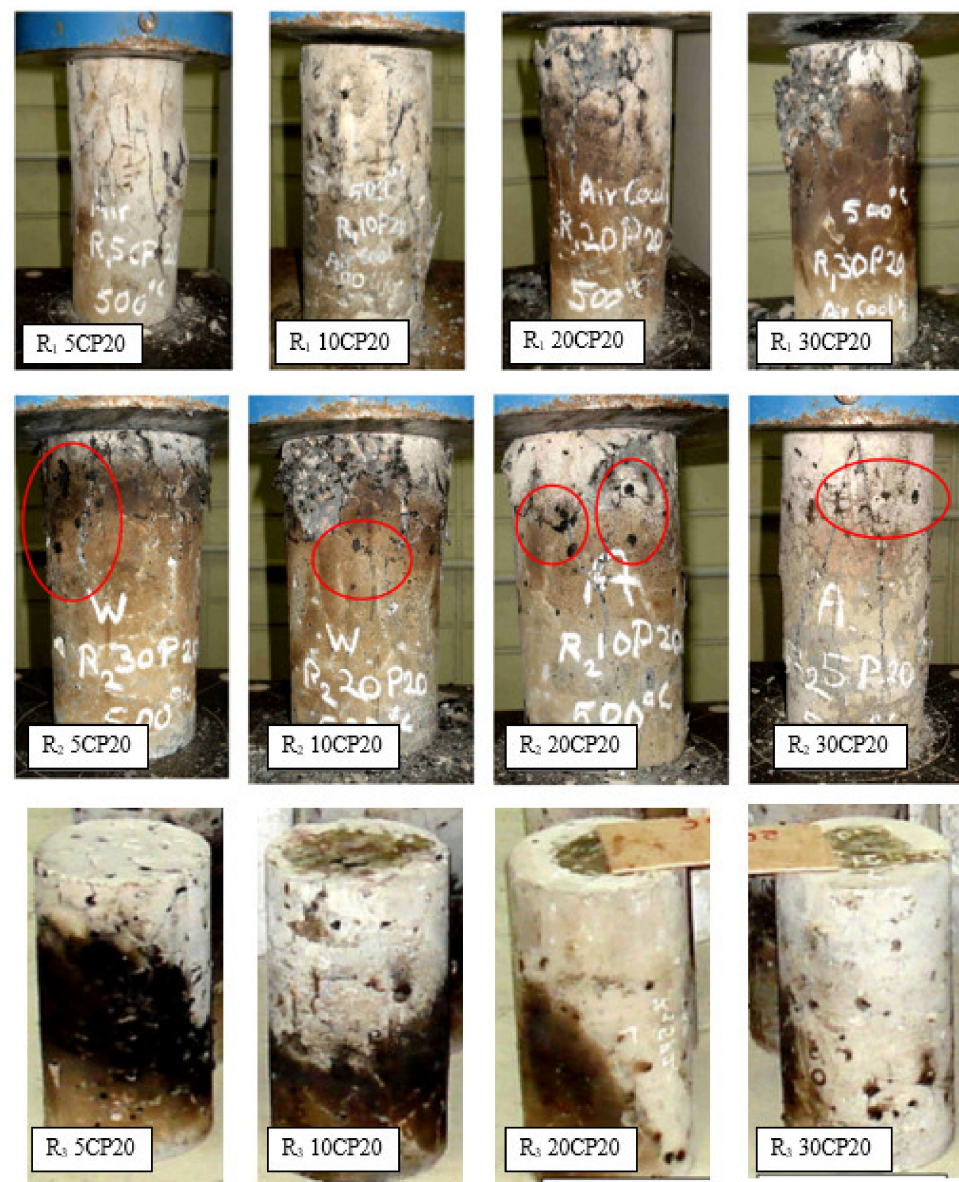
The surface of concrete containing 20% and 30% rubber particles types R1 and R2 showed crazing at 300 °C (Figure 12). The numbers of hairline cracks increased with the increase in rubber content, but these cracks were exiguous and tiny, and no soot was detected on the surface of the heated samples. The same observation was reported by Marques et al. [50] for rubberized concrete subjected to elevated temperatures. These cracks may have been due to the difference in the heat capacities of rubber and natural aggregates that caused different responses to high temperature, especially with decreasing moisture content. The impact of heating at 300 °C was more pronounced for concrete containing coarse rubber aggregates than for both fine types of rubber aggregates. The outer surface of the rubberized concrete specimens containing coarse rubber particles were significantly affected by cracks and pop-outs. Meanwhile, no surface pop-outs were observed in R1 and R2 concrete except some hairline cracks in concrete containing 20% and 30% fine rubber particles.



**Figure 12.** Physical characteristics of rubberized concrete after exposure to 300 °C.

In general, the addition of coarse rubber aggregate was found to result in more damage to the physical characteristics of the proposed concrete. An increase in the amount of rubber concentration further caused the appearance of cracks and spalling. As shown in Figure 13, when the rubberized concrete was exposed to 500 °C, the surface color significantly changed. The concrete containing lower concentrations of rubber particles (5 and 10%) became brighter than those samples heated at 300 °C with the same rubber particle content. This may be due to the water loss of the samples. Meanwhile, specimens with higher amounts of RTA (20 and 30%) exhibited a brown/black color because of the diffusion of carbon black that is part of the TRA. Furthermore, samples containing 20 and 30% of TRA particles were on fire (burning) at 500 °C when the furnace was opened. This was most likely due to the fact that the amount of TRA particles was enough to act as a flammable material, causing the concrete to burn as fuel at 500 °C. Despite the fact that visual inspection revealed R1 and R2 rubberized concrete to be burning at 500 °C, the R3 specimen was not on fire, regardless of the concentration of rubber particles.

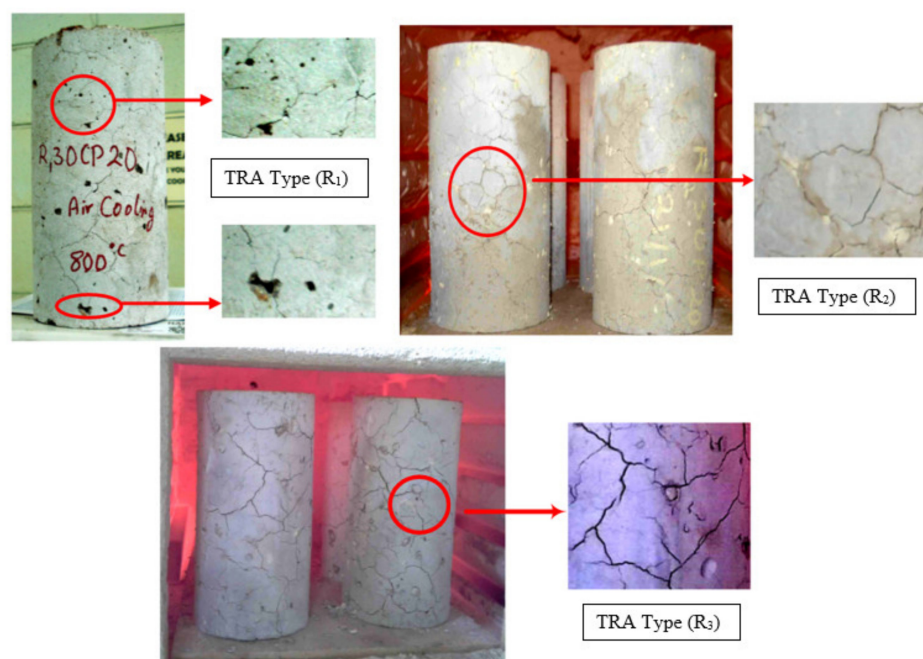
Figure 14 shows the physical condition of type R3 rubberized concrete when heated to 800 °C, in which the surface color and texture of concrete underwent considerable changes. The specimens were discolored to whitish grey, and all of them exhibited a network of cracks on the surface. As expected, the maximal dimensions and width of such cracks were more pronounced at 800 °C. Similar to the observations for R1 and R2 rubberized concrete at 800 °C, carbon black was not detected on the surface of the concrete. Moreover, no leakage of melted RTA was observed on the surface, however, numerous cavities and pores were found.



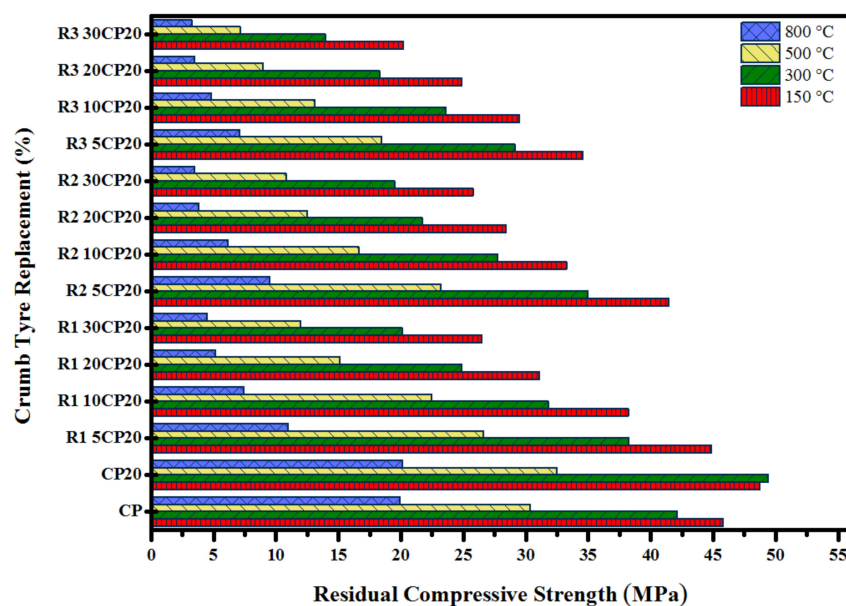
**Figure 13.** Physical characteristics of rubberized concrete after exposed to 500 °C.

### 3.3.2. Residual CS of Rubberized Concrete at Elevated Temperatures

Figure 15 displays the result of the residual CS of the proposed concrete subjected to elevated temperature with different curing regimes. The residual strength of the normal concrete steadily decreased as the temperature increased to 150 °C and above. At higher temperatures, severe and progressive compressive loss was observed. The major part of the CS loss occurred at 500 °C and above. The reduction in the CS values occurred beyond 400 °C, wherein calcium hydroxide started to decompose and lime was left behind [60]. For concrete containing 20% POFA, the CS increased to 48.75 and 49.4 MPa for 150 °C and 300 °C, respectively. Meanwhile, above 300 °C, the values of CS decreased to 32.5 and 20.1 MPa at 500 °C and 800 °C, respectively. This may be due to the dehydration of both calcium silicate hydrates and the decomposition of calcium hydroxide that occurred beyond 430 °C. The increase in the strength of POFA concrete could be ascribed to the loss of water and enhancement of the binding properties of C-H-S gel, or it may have been due to the production of extra C-S-H gel that contributed to the densification of the internal structure of the concrete by making it stiffer. A similar observation was made by Ismail et al. [58] and Li et al. [61].



**Figure 14.** Physical characteristics of rubberized concrete after exposure to 800 °C (pop-outs and cracks are shown by red circles).



**Figure 15.** Residual CS of the proposed rubberized concrete at various temperatures.

The residual CS values of all the R<sub>1</sub> rubberized concrete specimens except for R<sub>1</sub>5CP20 decreased at 150 °C. Furthermore, more serious deterioration of residual CS was found by increasing the level of rubber aggregate replacement at this temperature. The residual strength was systematically decreased by increasing both temperature and amount of rubber aggregate in the concrete. Meanwhile, a higher amount of rubber inclusion into the concrete resulted in a sharper reduction in strength compared with the one containing lower amounts of rubber particles. The rate of CS loss was higher for specimens exposed to temperatures above 150 °C. This reduction was more pronounced when the amount of rubber was increased. The obtained result showed a moderate decrease in the residual CS, of 59.82 and 58.23%, for 5 and 10% rubber content, respectively. Meanwhile, a greater reduction in the residual CS, of 46.7% and 42.8%, was observed in concrete made with

20 and 30% rubber, respectively. In brief, the proposed rubberized concrete suffered a significant loss at 800 °C, leading to a degradation in performance owing to the largest decrease in strength. This was because the rubber particles burned at high temperatures and decomposed at higher temperatures. Essentially, the rubber particles behaved as voids inside the concrete matrix, contributing to its performance degradation.

The minimal CS loss of all the R<sub>2</sub> rubberized concrete samples was obtained at 150 °C, wherein a higher amount of rubber resulted in a sharper reduction in strength, compared with concrete incorporated with a lower amount of rubber particles. The residual of compressive strength was in the range of 93.37 to 98.03%. The ratio of compressive strength loss became higher for specimens exposed to 300 °C, and this reduction was more pronounced when the amount of rubber was increased. The reduction in strength reached from 70.54 to 82.7% under air cooling. When the temperature exceeded 500 °C, the properties of the rubberized concrete deteriorated seriously, and the compressive strength was considerably decreased. For most levels of rubber incorporation, the relative residual compressive strength was not more than 54.77% of the original value, and only the samples with 5% R<sub>2</sub> rubber incorporation had a higher residual strength of 23 MPa, which was 54.8% of the original strength.

Similar to R<sub>1</sub> and R<sub>2</sub> rubberized concrete, minimal values of compressive strength loss of R<sub>3</sub> rubberized concrete were obtained at 150 °C. An increase in the rubber content resulted in a further deterioration of the residual compressive strength at elevated temperatures. The residual compressive strength was in the range of 90.08 to 96.51% under air cooling. In line with types R<sub>1</sub> and R<sub>2</sub> rubberized concrete, higher values of residual strength were obtained for 5% rubber content, whereas 30% rubber concentration resulted in additional strength loss. The rates of compressive strength loss became sharper after heating to 300 °C, and this reduction became more pronounced with the increasing amount of rubber. The reduction in strength reached from 81.26% to 59.02% for the increase of 5% to 30% of coarse rubber concentration under air cooling, respectively. The residual compressive strength decreased significantly when the specimens were exposed to 500 °C. For the 5% and 10% levels of coarse rubber aggregate replacement, the relative residual compressive strength values were 51.5 and 41.8% of their original values (before exposure to elevated temperature), respectively. For samples made with 20% and 30% R<sub>3</sub> rubber, the residual strength was 8.95 and 7.11 MPa, respectively, that is equal to 33.02 and 31.76% of compressive strength under normal conditions. These results were in agreement with the findings of Al-mutairi et al. [51], where it was reported that concrete containing 5% to 20% coarse rubber aggregate showed a high level of damage after exposure to 800 °C. Additionally, no significant difference was observed between the residual compressive strengths of concrete made with different amounts of rubber. Furthermore, a compressive strength lower than 5 MPa was observed for all percentages of rubber.

### 3.3.3. Impact of Temperature on the Weight Loss of Modified Rubberized Concrete

Figure 16 depicts the impact of temperature increase on the weight loss of modified rubberized concrete. The weight loss of specimens made with R<sub>1</sub> rubber particles was analyzed at 150, 300, 500, and 800 °C and presented as a percentage of the original weight of specimens at ambient temperature (prior to the heating process). The weight of concrete declined with the increase in temperature. The minimal mass loss was obtained at 150 °C for all percentages of rubber particle replacement. Meanwhile, a steady increase in weight loss in the range of 1.41 to 1.79% for the studied rubberized concrete was observed with the increase in rubber concentration. The weight loss of concrete within this range of temperature was mainly due to the moisture movement from the concrete surface to the surrounding environment [58]. The reduction in weight progressively increased at 300 °C, with percentages of 4.48% for 5% rubber incorporation, and 5.92% for 30% rubber replacement, under the air-cooling regime. Generally, the mass loss increased with the increasing amount of fine fiber rubber aggregate in the concrete at elevated temperature. In addition, the weight loss of concrete containing 10% rubber was in the range of 1.54%

to 11.76% after exposure to 150 °C to 800 °C, respectively. Similarly, the weight loss for concrete containing 30% rubber particles was in the range of 1.79% to 13.08% for 150 °C to 800 °C, respectively. This was due to the rubber aggregate decomposition at higher temperatures, that caused a higher mass loss of concrete containing a higher amount of TRA, than the one made with a lower amount of rubber.

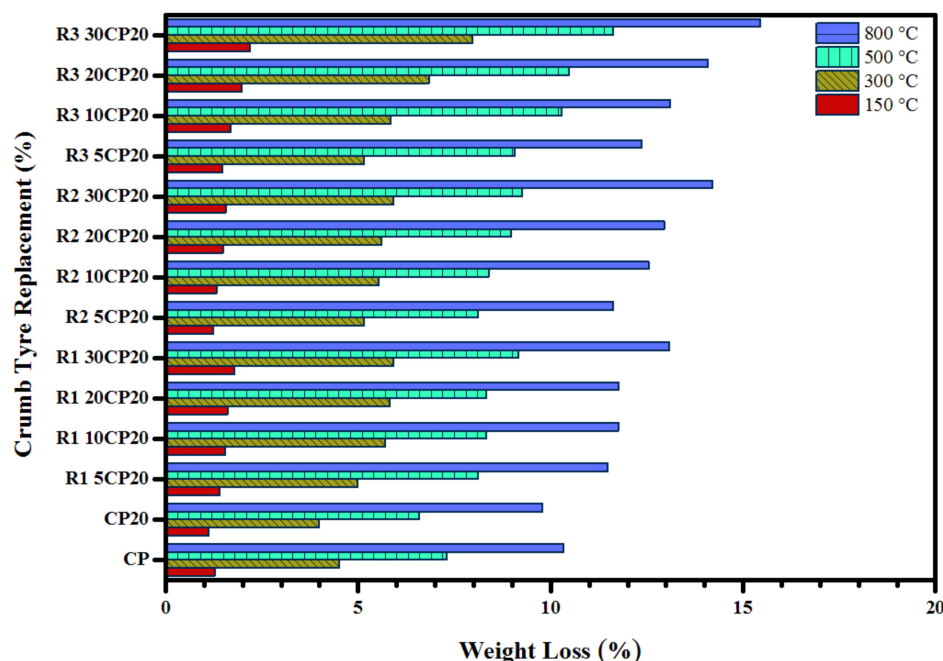


Figure 16. Weight loss of rubberized concrete at various elevated temperature.

Similar to R<sub>1</sub> rubberized concrete, the weight loss of concrete increased with increasing temperatures. Generally, the trend of mass loss of concrete containing fine granular rubber particles under the air-cooling regime was found to be in line with that of concrete made with fine fiber rubber particles. Nevertheless, the rate of weight loss was found to become gradually higher than that of fiber rubberized concrete at 500 °C and 800 °C. The density reductions at 150 °C were in the range of 1.24 to 1.56% for 5 to 30% rubber replacement, respectively. The weight loss was in the range of 5.16% to 5.92% at 300 °C. The same trend continued for 500 °C and 800 °C. The highest values of density reduction were obtained at 800 °C, which were in the range of 11.63 to 14.2%. As expected, the weight loss of R<sub>3</sub> rubberized concrete increased with the increase in temperatures (similar to R<sub>1</sub> and R<sub>2</sub> rubberized concrete types). In general, the trend of mass loss in R<sub>3</sub> rubberized concrete was in line with the two other types of rubberized concrete. However, the rate of weight loss was slightly higher than that of concrete containing fine fiber and fine granular particles. For all percentages of rubber content, the weight loss of concrete changed marginally after being heated to 150 °C, whereas the percentage of mass reduction increased with increasing rubber content. For instance, the weight loss values were in the range of 1.48 to 2.19%, corresponding to 5% to 30% rubber replacement, respectively. At 300 °C, the weight loss values were recorded to be in the range of 5.15 to 7.97%. This trend of reduction continued, and the percentages of mass loss were in the range of 9.06 to 11.63%, and 12.3 to 15.45%, at 500 °C and 800 °C, respectively. Lower values of density reduction were related to lower rubber content at all elevated temperatures. Generally, a higher concentration of rubber aggregate resulted in a greater density reduction at all elevated temperatures. In short, the observed increase in the values of mass loss after heating above 500 °C could be attributed to the vaporization of water in the concrete above 100 °C [62]. As a result, the rubber particles melted and gasified with the increase in temperature [63]. Meanwhile, the calcium–silicate–hydrate (C–S–H) gel was dehydrated and melted, whereas calcium hydroxide (Ca (OH)<sub>2</sub>) and calcium carbonate (CaCO<sub>3</sub>) were decomposed [64].

### 3.3.4. Ultrasonic Pulse Velocity (UPV) of Rubberized Concrete in Air-Cooling Regime

A comparative evaluation of the UPV values of the prepared rubberized concrete before and after exposure to elevated temperatures was performed (Table 4). Notably, the UPV value was reduced by increasing the rubber concentration in the concrete mixture under normal conditions (ambient temperature). This reduction could be attributed to the material properties of rubber aggregate, which naturally has the potential to dampen the wave velocity transfer. The UPV values at ambient temperature were between 4600 and 4300 m/s for 5 and 30% rubber content, respectively. According to Neville [60], these values were optimum to achieve excellent to good quality concrete. At 150 °C, the UPV values were in the range of 4575 to 3400 m/s for 5 to 30% rubber particle replacement, respectively. This trend continued at 300 °C and 500 °C. At 500 °C, the UPV values for 20 and 30% rubber content were at a very low range, reflecting that the quality of rubberized concrete was strongly affected by heating. The quality of concrete incorporated with high concentrations of rubber particles (20 and 30%) dropped sharply after being heated to 500 °C. Finally, at 800 °C, an excessive number of cracks and pores caused the values of UPV to be undetectable for 20% and 30% rubber content. The UPV values of the concrete incorporated with 20% and 30% fine fiber rubber aggregate was undetectable because of the large number of cracks and voids resulting from the decomposition of materials under high temperature. This observation supported the low values of residual compressive strength for R<sub>1</sub> 20CP20 and R<sub>1</sub> 30CP20. In brief, UPV values reduced with the increase in temperature [65]. This effect was more pronounced in concrete made with rubber aggregate, especially those exposed above 500 °C.

**Table 4.** UPV values of modified rubberized concrete exposed to elevated temperature.

| Specimens | Velocity at 27 °C (m/s) | Velocity at 150 °C (m/s) | Velocity at 300 °C (m/s) | Velocity at 500 °C (m/s) | Velocity at 800 °C (m/s) |
|-----------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| CP        | 4796                    | 4577                     | 3815                     | 1726                     | 1127                     |
| CP20      | 5070                    | 4784                     | 4074                     | 1829                     | 1197                     |
| R1 5CP20  | 4635                    | 4575                     | 3712                     | 1678                     | 1082                     |
| R1 10CP20 | 4542                    | 4320                     | 3153                     | 1229                     | 668                      |
| R1 20CP20 | 4319                    | 3703                     | 2774                     | 397                      | - *                      |
| R1 30CP20 | 4288                    | 3403                     | 2588                     | 252                      | - *                      |
| R2 5CP20  | 4555                    | 4365                     | 3577                     | 1988                     | 791                      |
| R2 10CP20 | 4376                    | 4061                     | 3660                     | 1896                     | - *                      |
| R2 20CP20 | 4474                    | 3703                     | 2839                     | 1343                     | - *                      |
| R2 30CP20 | 4291                    | 3097                     | 2300                     | 549                      | - *                      |
| R3 5CP20  | 4400                    | 4251                     | 3552                     | 1702                     | - *                      |
| R3 10CP20 | 4285                    | 4022                     | 2637                     | 341                      | - *                      |
| R3 20CP20 | 4230                    | 3181                     | 1857                     | - *                      | - *                      |
| R3 30CP20 | 4040                    | 2880                     | 1234                     | - *                      | - *                      |

\* The UPV value was not detectable due to concrete specimens severely affected by high temperature.

The quality of R<sub>2</sub> rubberized concrete was comparable to the one obtained for R<sub>1</sub> rubberized concrete, wherein the UPV value reduced with the increase in rubber concentration in the mixture under normal conditions (ambient temperature). The UPV value of modified concrete at ambient temperature was 4576 m/s for 5% of rubber content, considered as excellent quality. However, this value dropped to 4273 m/s at 30% rubber content, thus, classified within the range of good quality according to Neville [60]. These values were slightly lower than those obtained for R<sub>1</sub> rubberized concrete at all levels of rubber replacement. At 150 °C, the UPV values of concrete were in the range of 4365 m/s to 3097 m/s

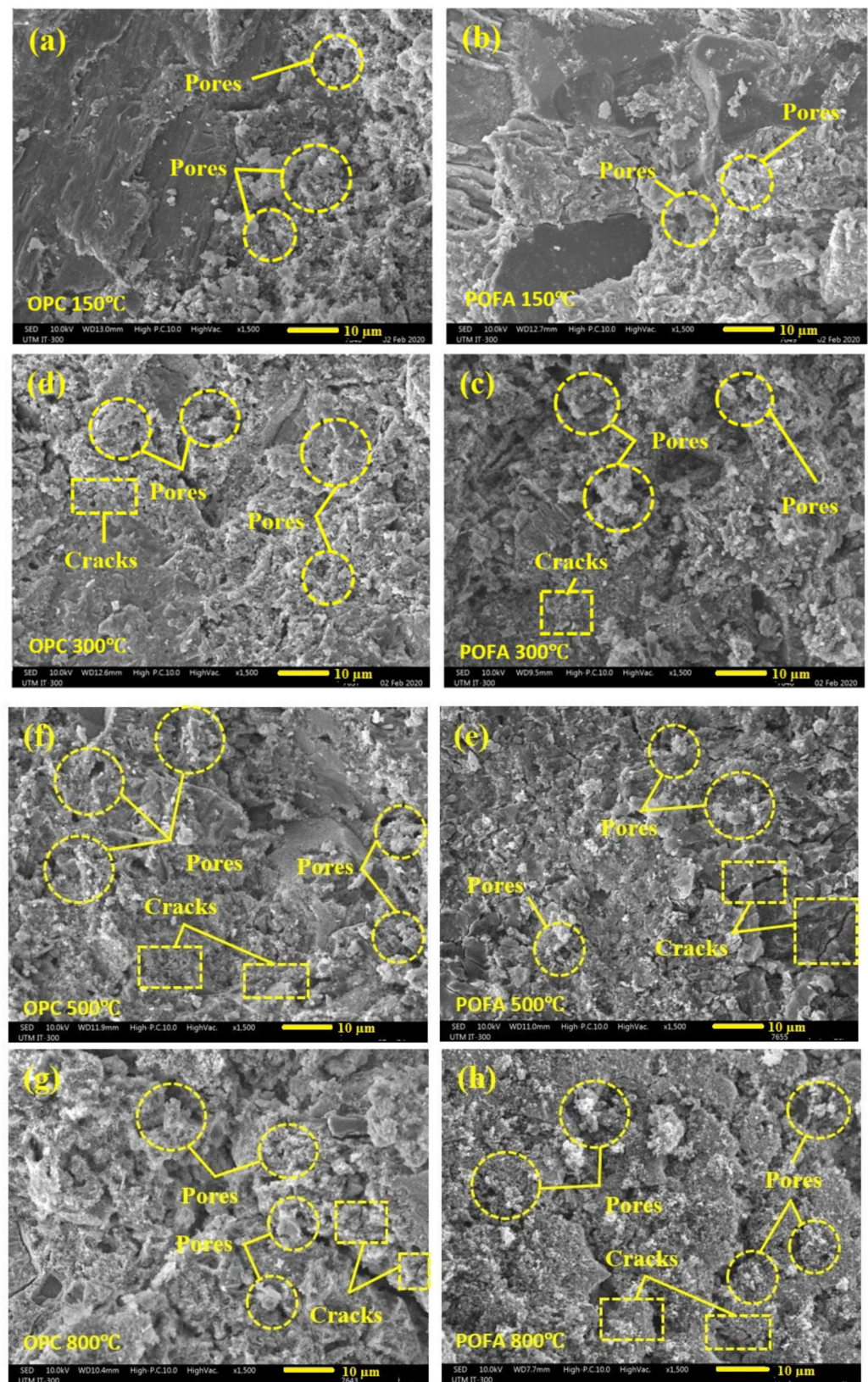
for 5% to 30% rubber content, respectively. The  $R_2$  rubberized concrete was significantly affected at 500 °C wherein the UPV values ranged from 1988 m/s to 549 m/s corresponding to 5% to 30% rubber, respectively, under the air-cooling regime. At 800 °C, the UPV values were not detectable for all concrete made with more than 5% rubber. This was due to the excessive quantity of cracks and pores that remained after the complete decomposition of the rubber aggregates. Consequently, the recorded UPV values were considered to be very poor quality for both cooling regimes.

The quality evaluation of  $R_3$  rubberized concrete was conducted using a procedure similar to that used for other rubberized concrete. The UPV values at the ambient temperature were in range of 4425 to 4040 m/s, corresponding to 5 to 30% rubber content. The UPV results clearly showed that the size and amount of rubber particles could influence the UPV values, and an increase in the rubber content could further deteriorate the UPV values of the resulting concrete, indicating that the coarser rubber particles could lower the UPV values. At 150 °C, the UPV values dropped slightly to 4251 m/s for concrete made with 5% rubber, whereas the UPV values became moderately lower (4022 m/s) for concrete containing 10% rubber. The results of the UPV test for concrete made with 20 and 30% coarse rubber indicated a steep reduction compared with the normal values (before heating). Type  $R_3$  rubberized concrete was significantly affected at 500 °C. The values of UPV were 1702 and 341 m/s for concrete made with 5% and 10% rubber. Meanwhile, the UPV value was not detectable for concrete containing 20% and 30%  $R_3$  rubber aggregate due to the large number of cracks and pores that appeared after exposure to 500 °C. At 800 °C, the values of UPV were not detectable for all concrete specimens regardless of rubber content. These results demonstrated that type  $R_3$  rubberized concrete significantly deteriorated at 800 °C. These results supported the observation of the residual compressive strength test, and the visual inspection.

### 3.3.5. Effect of Elevated Temperatures on Microstructures of Modified Rubberized Concrete

Figure 17 shows an SEM image indicating the effect of POFA as an OPC replacement, on the surface microstructures of concrete exposed to elevated temperatures. The concrete exposed to 500 °C showed some small pores and continuous structure without micro cracks. However, the OPC concrete (Figure 17f) showed lower resistance to elevated temperature, wherein the structural deterioration and number of pores formed was higher than the concrete made with POFA (Figure 17e). Concrete exposed to 900 °C displayed lower structural density compared with the concrete exposed to 500 °C, wherein the number and width of pores and cracks increased with the increase in temperature. Similarly, the concrete made with POFA (Figure 17h) showed a lower number of pores, cracks and less deterioration compared with concrete made with OPC (Figure 17g) exposed to the same temperature. At elevated temperatures, the matrices of POFA showed higher resistance and better performance than OPC.

The effect of OPC replaced with 20% POFA, on modified concrete exposed to elevated temperatures (500 °C), is illustrated in Figure 18. The XRD analysis demonstrated that the concrete's composition was significantly affected by high temperatures. In both tradition concrete (0% POFA) and modified concrete (20% POFA) specimens exposed to temperatures of 500 °C, ettringite and gypsum were produced. Furthermore, the intensities of  $\text{SiO}_2$  and  $\text{CaCO}_3$  were significantly lower in 0% POFA specimens than in 20% POFA specimens. Furthermore, the dehydroxylation of calcium hydroxide was also observable, resulting in the complete collapse of the concrete composition as calcium hydroxide degraded and lost its place in the matrix. This degradation led to the concrete's reduced performance and strength loss at elevated temperatures. This indicates that a concrete matrix which includes 20% POFA may have a significantly improved performance at elevated temperatures, as the dehydroxylation of the cement matrix may be better avoided [66].



**Figure 17.** SEM image at elevated temperature for concretes containing: (a) OPC at 150 °C, (b) POFA at 150 °C, (c) OPC at 300 °C, (d) POFA at 300 °C, (e) OPC at 500 °C, (f) POFA at 500 °C, (g) OPC at 900 °C, (h) POFA at 900 °C.

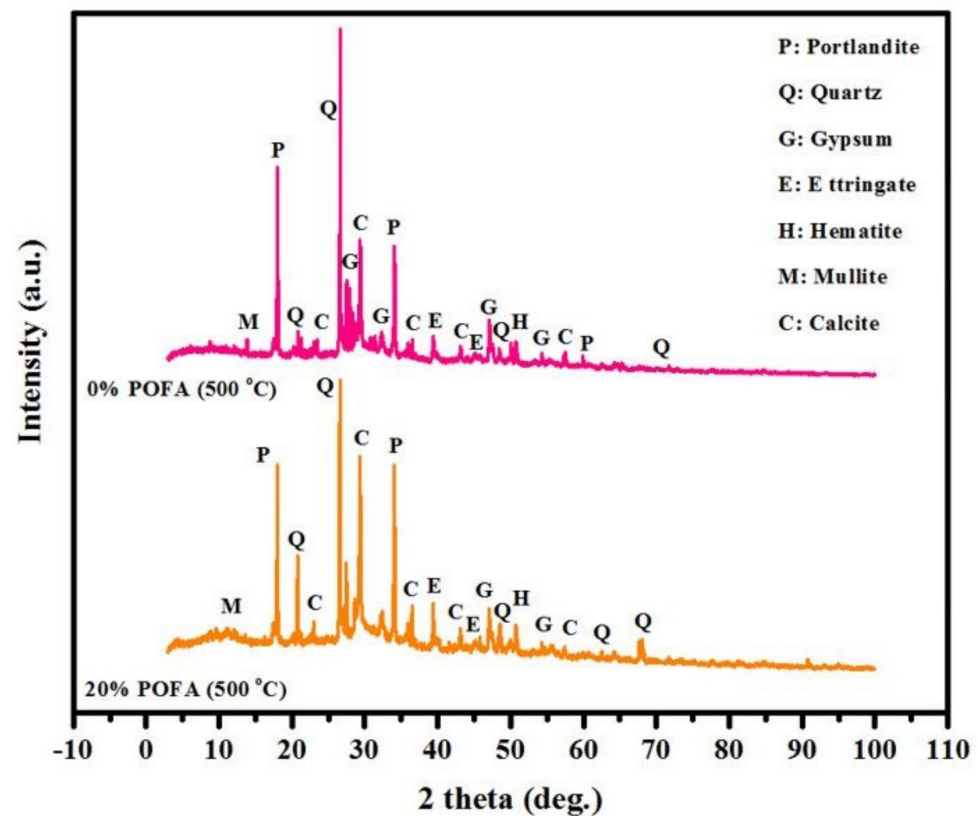


Figure 18. Effect of 20% POFA as OPC replacement on XRD of modified concrete exposed to 500 °C.

### 3.3.6. Relationship between UPV Values and Residual Compressive Strength of Rubberized Concrete

A relationship between the UPV values of the rubberized concrete and its residual compressive strength at various elevated temperatures was ascertained (Figures 19–21). The linear regression method was applied to estimate the relative residual compressive strength at various temperatures and UPV values. The proposed equations were plotted for concretes containing 5% to 30% rubber at elevated temperatures. The UPV values and compressive strength at ambient temperature were included in the calculation to improve the clarity of the relationship for concretes made using various amounts of fine fiber rubber particles. The coefficient of determination  $R^2$  was presented for every equation that showed the proportion of the variance of residual compressive strength predictable from the UPV values. This value of  $R^2$  signified the strength of the linear association between residual compressive strength and UPV values for all elevated temperature levels relative to the amount of rubber aggregate. Linear correlation can be defined by Equations (2)–(5), with the coefficient of determination  $R^2$  falling between 0.902 and 0.988 for concrete containing various amounts of type R<sub>1</sub> rubber aggregate.

$$R1\ 5CP20: Y_{RCS-A} = 0.0082 X_{UPV-A} + 6.6504; R^2 = 0.9169 \quad (2)$$

$$R1\ 10CP20: Y_{RCS-A} = 0.0068 X_{UPV-A} + 7.8344; R^2 = 0.9023 \quad (3)$$

$$R1\ 20CP20: Y_{RCS-A} = 0.0045 X_{UPV-A} + 13.143; R^2 = 0.9884 \quad (4)$$

$$R1\ 30CP20: Y_{RCS-A} = 0.0042 X_{UPV-A} + 10.703; R^2 = 0.9698 \quad (5)$$

where  $Y_{RCS-A}$  is the residual compressive strength and  $X_{UPV-A}$  is the ultrasonic pulse velocity.

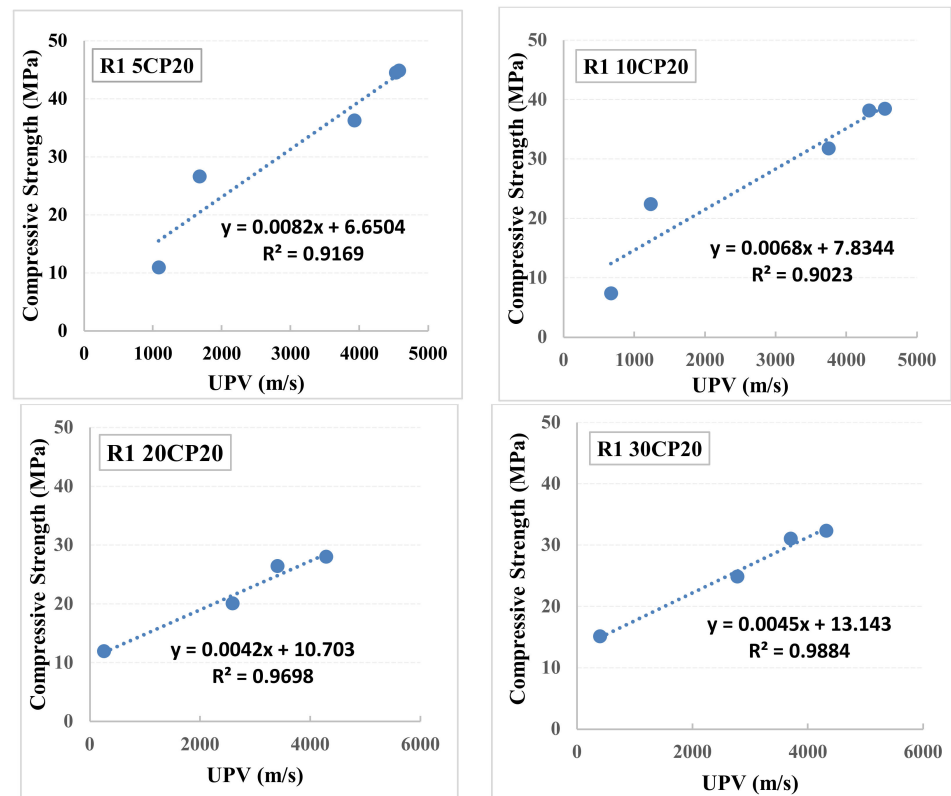


Figure 19. Correlation between UPV values and residual compressive strength of type R<sub>1</sub> rubberized concrete.

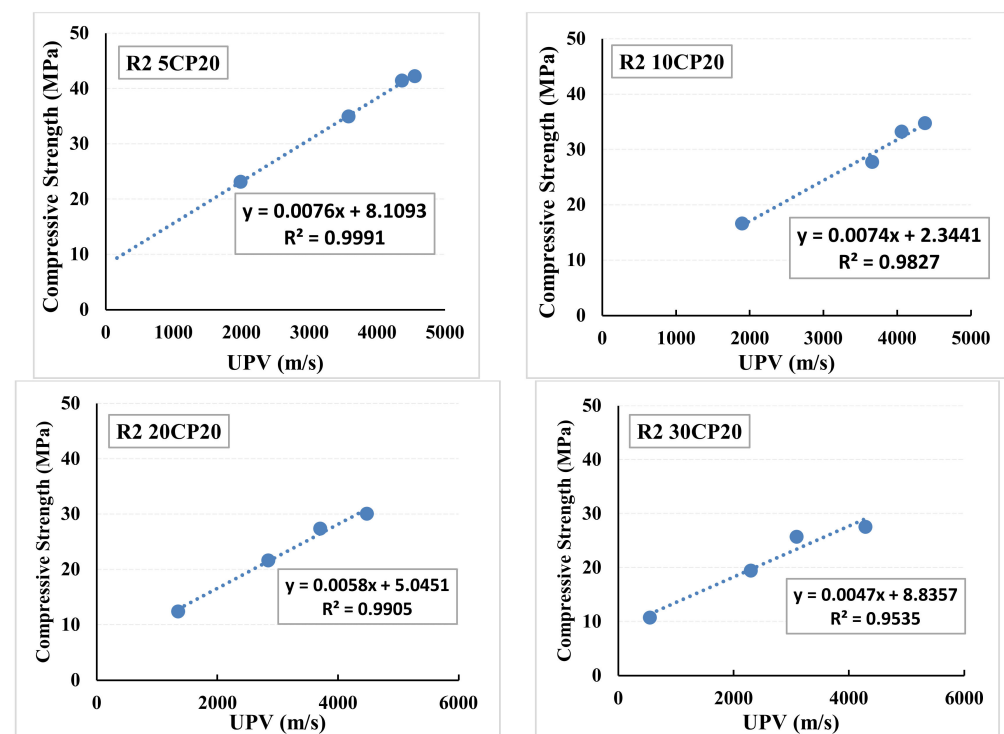
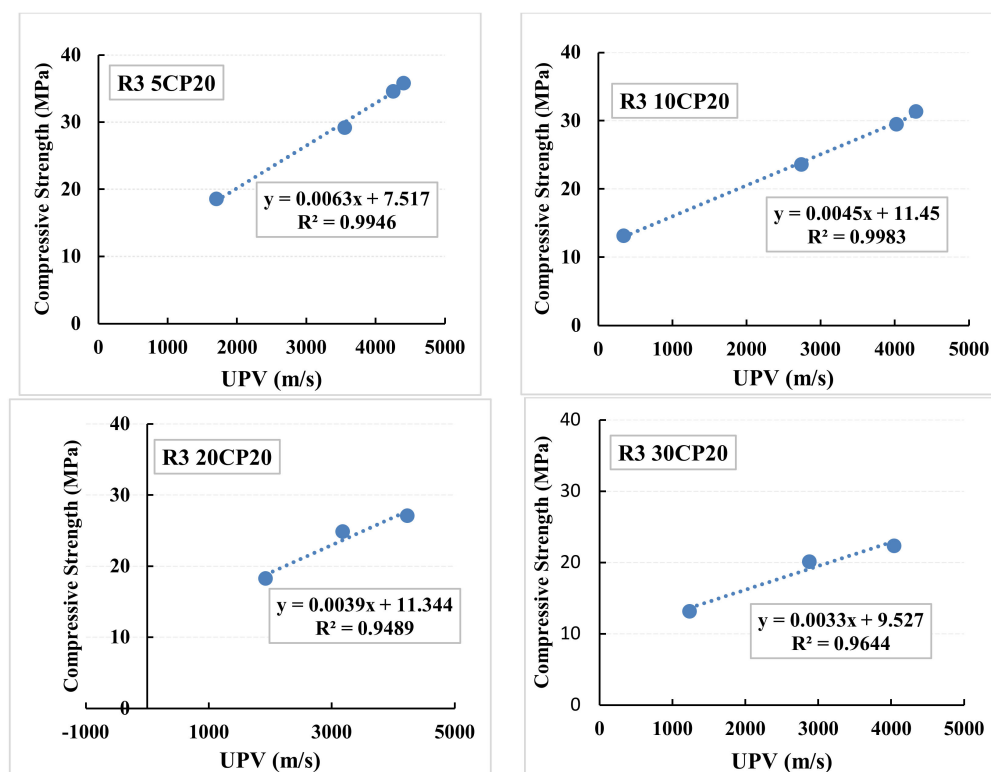


Figure 20. Correlation between UPV values and residual compressive strength for R2 rubberized concrete.



**Figure 21.** Correlation between UPV values and residual compressive strength for R<sub>3</sub> rubberized concrete.

The correlation between UPV values and residual compressive strength were well-fitted to the proposed equations, achieving the values of  $R^2$  in the range of 0.902 to 0.988 and 0.883 to 0.937 for air cooling and water cooling, respectively. The obtained correlations can be used to determine the residual compressive strength of concrete at a given temperature using a UPV test compressive strength with appropriate precision.

Similar to R<sub>1</sub> concrete, the linear regression method was applied to estimate the relative residual compressive strength at various temperatures and UPV values for R<sub>2</sub> rubberized concrete at elevated temperatures. The values of  $R^2$  were also presented for every equation. Linear correlation can be defined by Equations (6)–(9), with the values of  $R^2$  in the range of 0.95 and 0.99 for concrete containing various amounts of type R<sub>2</sub> rubber aggregate.

$$R2\ 5CP20: Y_{RCS-A} = 0.0076 X_{UPV-A} + 8.1093; R^2 = 0.9991 \quad (6)$$

$$R2\ 10CP20: Y_{RCS-A} = 0.0074 X_{UPV-A} + 2.3441; R^2 = 0.9827 \quad (7)$$

$$R2\ 20CP20: Y_{RCS-A} = 0.0058 X_{UPV-A} + 5.0451; R^2 = 0.9905 \quad (8)$$

$$R2\ 30CP20: Y_{RCS-A} = 0.0047 X_{UPV-A} + 8.8357; R^2 = 0.9535 \quad (9)$$

Figure 21 illustrates the linear relationship between the UPV values and residual compressive strengths of concrete containing various amounts of coarse granular rubber aggregate at elevated temperatures. Given the undetectable UPV values for some samples, the correlation was considered only for temperatures beyond 500 °C for both cooling regimes. As for R<sub>1</sub> and R<sub>2</sub> rubberized concrete, the linear regression method was applied to estimate the relative residual compressive strength at various temperatures and UPV values for concrete containing coarse rubber particles. The values of  $R^2$  were also presented for every equation. Linear correlation can be defined by Equations (10)–(13), with the values of  $R^2$  in the range of 0.94 and 0.99 relative to various amounts of rubber aggregate, wherein these coefficients represented a strong relationship.

$$R3\ 5CP20: Y_{RCS-A} = 0.0063 X_{UPV-A} + 7.517; R^2 = 0.9946 \quad (10)$$

$$R3\ 10CP20: Y_{RCS-A} = 0.0045 X_{UPV-A} + 11.45; R^2 = 0.9983 \quad (11)$$

$$R3\ 20CP20: Y_{RCS-A} = 0.0039 X_{UPV-A} + 11.344; R^2 = 0.9439 \quad (12)$$

$$R3\ 30CP20: Y_{RCS-A} = 0.0033 X_{UPV-A} + 9.527; R^2 = 0.9644 \quad (13)$$

The values of  $R^2$  exhibited a strong correlation between residual compressive strength and UPV values. It was concluded that the UPV test can be used to estimate the residual compressive strength of concrete with considerable accuracy at a given temperature by applying the given equation relative to the concentration of rubber aggregate.

### 3.4. Impedance Measurement

The ability of a material to convert sound energy and absorb sound is known as the sound absorption property (Figure 22). The fraction of sound energy absorbed by a material is defined by the sound absorption coefficient ( $\alpha$ ). It is expressed as a value between 0 and 1.0. The highest value of 1.0 indicates perfect absorption, indicating that the material has the ability to totally absorb sound with no reflection. The lowest value of 0.0 signifies a total reflection of sound and zero absorption by the material. In this work, the sound absorption of modified rubberized concrete made using the three types of rubber particles was evaluated under two different ranges of frequency, namely, 1000 Hz, and between 1000 Hz and 5000 Hz. The sound absorption property of the modified rubberized concrete is generally presented and demonstrated by complex  $\alpha$ -value graphs at different frequency ranges, involving calculations over several frequencies. For the sake of simplicity, the absorption ability of concrete in this study was represented by a single value called the “noise reduction coefficient” (NRC). For CP20, the NRC decreased as POFA was added to the concrete. This reduction was mainly due to the thickness narrowing by POFA (at optimum content of 20%) at the interfacial transition zone of the cementitious material. Hence, the air content of concrete decreased when 20% POFA was added to the concrete. Therefore, the ability of sound absorption declined and sound was not absorbed, as it would for conventional concrete. A similar observation was made by Mohammed et al. [67] for concrete enclosing pozzolanic material (silica fume).

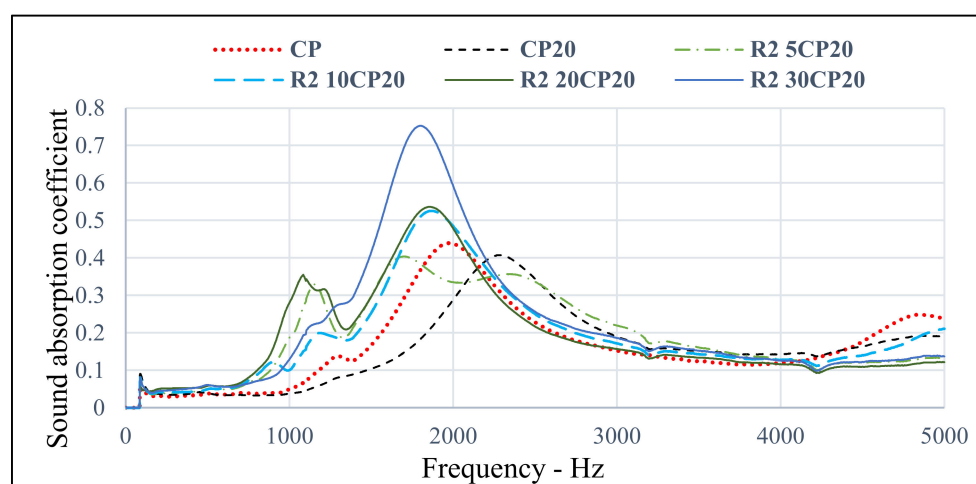
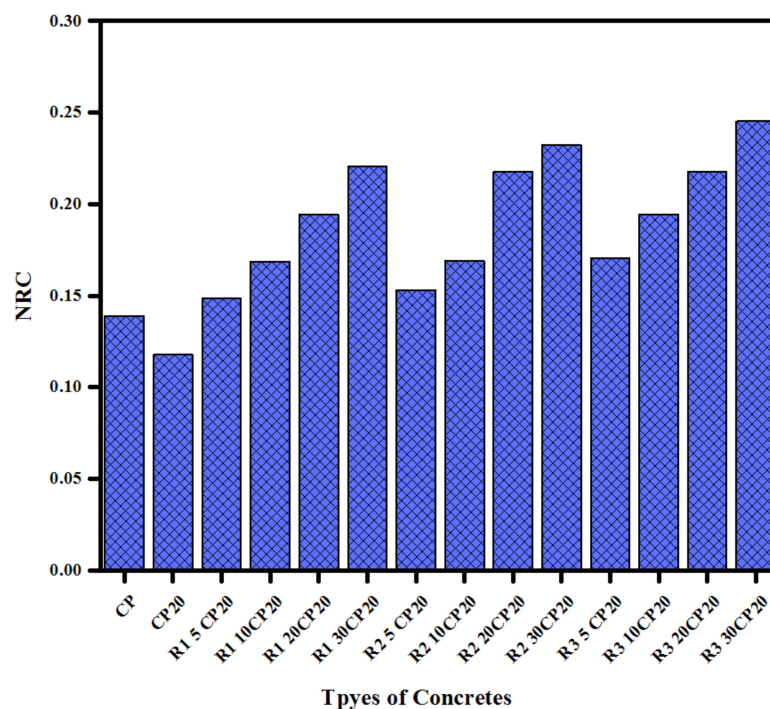


Figure 22. Sound absorption coefficient of modified concrete contains fine-granular TRAs.

The results of NRC for various rubberized concretes are shown in Figure 23. The values of  $\alpha$  for CP20 were slightly higher than for conventional concrete (CP) at a low frequency region (125 to 500 Hz). At higher frequencies, normal concrete showed moderately higher  $\alpha$  values than CP20. Moreover, CP20 exhibited better results for frequencies above 2250 Hz. Overall, CP showed better performance (NRC = 0.139) than CP20 (NRC = 0.117). In terms of NRC

values, R<sub>1</sub> rubberized concrete showed superior sound resistance properties compared with normal concrete. Furthermore, the results indicated a systematic progress in sound resistance as the rubber content was increased. The NRC values for R<sub>1</sub> rubberized concrete made with 5 to 30% rubber particles were in the range of 0.1484 to 0.2207. With the increase in rubber concentration, the sound absorption values at both low and high frequencies were improved.



**Figure 23.** NRC values for different types of concrete mixes.

In order to analyze the sound absorption characteristics of concrete containing fine granular (R<sub>2</sub>) rubber particles, the absorption coefficient was measured for various frequencies (100 to 5000 Hz) by the impedance tube method. The results indicated that the absorption coefficient became maximal at the range of 1500–2000 Hz for R<sub>2</sub> 5CP20, R<sub>2</sub> 10CP20, R<sub>2</sub> 20CP20, and R<sub>2</sub> 30CP20. The highest absorption coefficient was obtained at the maximum rubber aggregate content in the concrete. In addition, for the frequencies lower than 1500 Hz, R<sub>2</sub> 20CP20 and R<sub>2</sub> 5CP20 concrete showed better performance in sound absorption property compared with other specimens. The value of NRC was 0.153, 0.169, 0.217, and 0.232 for concrete made with 5, 10, 20 and 30% type R<sub>2</sub> rubber particles, respectively. It was observed that the NRC values increased with the increase in rubber in the concrete. It has been shown [68] that the sound absorption coefficient can be improved by increasing the rubber aggregate fraction in concrete. The reason that NRC improved by adding rubber aggregate can be explained by the increase in the air content of concrete with higher concentrations of rubber aggregate, along with the natural properties of rubber particles for absorption of and reduction in sound energy. The best NRC results were obtained for R<sub>3</sub> 30CP20, which were 0.170, 0.194, 0.218, and 0.245 for concrete made with 5, 10, 20, and 30% rubber particles, respectively. It was asserted that a systematic increase in sound absorption could be achieved by introducing more rubber particles. Furthermore, the results showed that the size and type of rubber particles could significantly affect the sound absorption properties. The coarse rubber aggregate showed a higher potential of sound proofing property than fiber rubber aggregate. Moreover, the granular type of rubber displayed a better performance than the fiber type of rubber particles. The superior results of coarse rubber particles on sound proofing property can be attributed to the higher air content of concrete incorporating coarse rubber particles (R<sub>3</sub>) in comparison with the fine

rubber aggregates. The coarse rubber particles also had superior abilities to absorb and dampen higher energy.

#### 4. Conclusions

The experimental results and detailed analyses enabled us to conclude the following:

1. The water absorption properties of the proposed rubberized concrete indicated an increase in the permeability and total porosity with the increase in rubber content in the mixture. Incorporation of coarse rubber aggregate showed a greater ability to increase the permeability properties of the rubberized concrete than fine rubber particles;
2. A rapid chloride ion penetration result revealed that the studied rubberized concrete was satisfactory. Nevertheless, incorporation of rubber aggregates was found to increase chloride penetration, which was more pronounced in coarse rubber aggregate-included concrete. Generally, rubberized concrete was classified as achieving a low to moderate level of chloride penetration, following the ASTM standard;
3. The elevated temperatures had significant effects on the performance of rubberized concrete wherein the post-fire properties of concrete made with rubber particles was considerably affected. The rubberized concrete showed satisfactory performance up to 500 °C, wherein all types of rubber concrete effectively lost performance at 800 °C. A visual inspection revealed that concrete made with rubber particles was greatly influenced by rubber aggregate content, wherein concrete with higher amounts of rubber particles displayed more carbon black. With the increase in temperatures, the residual compressive strength of the rubberized concrete revealed a progressive deterioration. In addition, the UPV values decreased in line with the compressive strength;
4. A systematic improvement of NRC was achieved by increasing the rubber content, useful for the development of sound-proof concrete material required for various low-cost structural applications. It was asserted that the present study may provide higher standards of residential buildings in the provision of quiet spaces;
5. Coarse rubber aggregates were found to be the best NCR among the three types of rubber particles;
6. In short, the proposed rubberized concrete containing POFA as cement replacement can be a potential candidate in the construction industry owing to its excellent durability and acoustic performance, thus, minimizing landfill and environmental problems.

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## References

1. Thomas, B.S.; Gupta, R.C.; Panicker, V.J. Recycling of waste tire rubber as aggregate in concrete: Durability-related performance. *J. Clean. Prod.* **2016**, *112*, 504–513. [\[CrossRef\]](#)
2. Thomas, B.S.; Gupta, R.C. A comprehensive review on the applications of waste tire rubber in cement concrete. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1323–1333. [\[CrossRef\]](#)
3. Rashid, K.; Yazdanbakhsh, A.; Rehman, M.U. Sustainable selection of the concrete incorporating recycled tire aggregate to be used as medium to low strength material. *J. Clean. Prod.* **2019**, *224*, 396–410. [\[CrossRef\]](#)
4. Ferronato, N.; Torretta, V. Waste mismanagement in developing countries: A review of global issues. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1060. [\[CrossRef\]](#)
5. Mhaya, A.M.; Baghban, M.H.; Faridmehr, I.; Huseien, G.F.; Abidin, A.R.Z.; Ismail, M. Performance evaluation of modified rubberized concrete exposed to aggressive environments. *Materials* **2021**, *14*, 1900. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Brown, K.M.; Cummings, R.; Mrozek, J.R.; Terrebonne, P. Scrap tire disposal: Three principles for policy choice. *Nat. Resour. J.* **2001**, *41*, 9–22.
7. Akbas, A.; Yuhana, N.Y. Recycling of Rubber Wastes as Fuel and Its Additives. *Recycling* **2021**, *6*, 78. [\[CrossRef\]](#)
8. Sienkiewicz, M.; Janik, H.; Borzędowska-Labuda, K.; Kucińska-Lipka, J. Environmentally friendly polymer-rubber composites obtained from waste tyres: A review. *J. Clean. Prod.* **2017**, *147*, 560–571. [\[CrossRef\]](#)
9. Shakya, P.R.; Shrestha, P.; Tamrakar, C.S.; Bhattarai, P.K. Studies on potential emission of hazardous gases due to uncontrolled open-air burning of waste vehicle tyres and their possible impacts on the environment. *Atmos. Environ.* **2008**, *42*, 6555–6559. [\[CrossRef\]](#)
10. De Brito, J.; Saikia, N. *Recycled Aggregate in Concrete: Use of Industrial, Construction and Demolition Waste*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; pp. 156–216.
11. Ahmad, J.; Zhou, Z.; Majidi, A.; Alqurashi, M.; Deifalla, A.F. Overview of Concrete Performance Made with Waste Rubber Tires: A Step toward Sustainable Concrete. *Materials* **2022**, *15*, 5518. [\[CrossRef\]](#)
12. Association, R.M. *US Scrap Tire Management Summary*; Rubber Manufacturers Association: Washington, DC, USA, 2014.
13. Association, R.M. Scrap tire markets in the United States. *9th Bienn. Rep.* **2009**, *5*, 1–105.
14. Mhaya, A.; Abidin, A.; Sarbini, N.; Ismail, M. Role of crumb tyre aggregates in rubberised concrete contained granulated blast-furnace slag. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *220*, 012029. [\[CrossRef\]](#)
15. Ross, D.E. Use of waste tyres in a circular economy. *Waste Manag. Res.* **2020**, *38*, 1–3. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Rubber Manufacturers Association. *Scrap Tire Markets in the United States*, 2005 ed.; Rubber Manufacturers Association: Washington, DC, USA, 2006; Volume 12.
17. Qaidi, S.M.; Mohammed, A.S.; Ahmed, H.U.; Faraj, R.H.; Emad, W.; Tayeh, B.A.; Althoey, F.; Zaid, O.; Sor, N.H. Rubberized geopolymer composites: A comprehensive review. *Ceram. Int.* **2022**, *48*, 24234–24259. [\[CrossRef\]](#)
18. Eldin, N.N.; Senouci, A.B. Rubber-tire particles as concrete aggregate. *J. Mater. Civ. Eng.* **1993**, *5*, 478–496. [\[CrossRef\]](#)
19. Li, G.; Stubblefield, M.A.; Garrick, G.; Eggers, J.; Abadie, C.; Huang, B. Development of waste tire modified concrete. *Cem. Concr. Res.* **2004**, *34*, 2283–2289. [\[CrossRef\]](#)
20. Snelson, D.; Kinuthia, J.; Davies, P.; Chang, S.-R. Sustainable construction: Composite use of tyres and ash in concrete. *Waste Manag.* **2009**, *29*, 360–367. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Mhaya, A.M.; Fahim Huseien, G.; Faridmehr, I.; Razin Zainal Abidin, A.; Alyousef, R.; Ismail, M. Evaluating mechanical properties and impact resistance of modified concrete containing ground Blast Furnace slag and discarded rubber tire crumbs. *Constr. Build. Mater.* **2021**, *295*, 123603. [\[CrossRef\]](#)
22. Kundan, P.; Sharma, S. Rubberized cemented concrete composites: A review. *Mater. Today: Proc.* **2021**, *44*, 4838–4842. [\[CrossRef\]](#)
23. Roychand, R.; Gravina, R.J.; Zhuge, Y.; Ma, X.; Youssf, O.; Mills, J.E. A comprehensive review on the mechanical properties of waste tire rubber concrete. *Constr. Build. Mater.* **2020**, *237*, 117651. [\[CrossRef\]](#)
24. Siddika, A.; Al Mamun, M.A.; Alyousef, R.; Amran, Y.M.; Aslani, F.; Alabduljabbar, H. Properties and utilizations of waste tire rubber in concrete: A review. *Constr. Build. Mater.* **2019**, *224*, 711–731. [\[CrossRef\]](#)
25. Mhaya, A.M.; Baharom, S.; Huseien, G.F. Improved strength performance of rubberized Concrete: Role of ground blast furnace slag and waste glass bottle nanoparticles amalgamation. *Constr. Build. Mater.* **2022**, *342*, 128073. [\[CrossRef\]](#)
26. Imbabi, M.S.; Carrigan, C.; McKenna, S. Trends and developments in green cement and concrete technology. *Int. J. Sustain. Built Environ.* **2012**, *1*, 194–216. [\[CrossRef\]](#)
27. Samadi, M.; Baghban, M.H.; Kubba, Z.; Faridmehr, I.; Abdul Shukor Lim, N.H.; Benjeddou, O.; Ariffin, N.F.B.; Huseien, G.F. Flexural Behavior of Reinforced Concrete Beams under Instantaneous Loading: Effects of Recycled Ceramic as Cement and Aggregates Replacement. *Buildings* **2022**, *12*, 439. [\[CrossRef\]](#)
28. Mhaya, A.M.; Huseien, G.F.; Abidin, A.R.Z.; Ismail, M. Long-term mechanical and durable properties of waste tires rubber crumbs replaced GBFS modified concretes. *Constr. Build. Mater.* **2020**, *256*, 119505. [\[CrossRef\]](#)
29. Hamzah, H.K.; Joudah, Z.H.; Georgescu, D.P.; Khalid, N.H.A.; Huseien, G.F. Laboratory evaluation of alkali-activated mortars modified with nanosilica from glass bottle wastes. *Mater. Today Proc.* **2021**, *46*, 2098–2104. [\[CrossRef\]](#)
30. Rafieizonooz, M.; Salim, M.R.; Mirza, J.; Hussin, M.W.; Khan, R.; Khankhaje, E. Toxicity characteristics and durability of concrete containing coal ash as substitute for cement and river sand. *Constr. Build. Mater.* **2017**, *143*, 234–246. [\[CrossRef\]](#)

31. Nurfarhanna, A.; Hani, A.S.; Hairi, O.M.; Zalipah, J.; Azlina, A.N.; Norhafizah, S.; Anizahyati, A. The Compressive Strength and Water Absorption of Railway's Concrete Sleepers Containing Palm Oil Fuel Ash (POFA) as a Cement Replacement Material. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1200*, 012001. [\[CrossRef\]](#)
32. Huseien, G.F.; Sam, A.R.M.; Algaifi, H.A.; Alyouef, R. Development of a sustainable concrete incorporated with effective microorganism and fly Ash: Characteristics and modeling studies. *Constr. Build. Mater.* **2021**, *285*, 122899. [\[CrossRef\]](#)
33. Alaskar, A.; Shah, S.; Keerio, M.A.; Phulpoto, J.A.; Baharom, S.; Assilzadeh, H.; Alyousef, R.; Alabduljabbar, H.; Mohamed, A.M. Development of Pozzolan material from clay. *Adv. Concr. Constr.* **2020**, *10*, 301–310.
34. Huseien, G.F.; Sam, A.R.M.; Shah, K.W.; Mirza, J. Effects of ceramic tile powder waste on properties of self-compacted alkali-activated concrete. *Constr. Build. Mater.* **2020**, *236*, 117574. [\[CrossRef\]](#)
35. Huseien, G.; Ismail, M.; Tahir, M.; Mirza, J.; Hussein, A.; Khalid, N.; Sarbini, N. Performance of sustainable alkali activated mortars containing solid waste ceramic powder. *Chem. Eng. Trans.* **2018**, *63*, 673–678.
36. Salman, N.M.; Ma, G.; Ijaz, N.; Wang, L. Importance and potential of cellulosic materials and derivatives in extrusion-based 3D concrete printing (3DCP): Prospects and challenges. *Constr. Build. Mater.* **2021**, *291*, 123281. [\[CrossRef\]](#)
37. Shafigh, P.; Mahmud, H.B.; Jumaat, M.Z.; Zargar, M. Agricultural wastes as aggregate in concrete mixtures—A review. *Constr. Build. Mater.* **2014**, *53*, 110–117. [\[CrossRef\]](#)
38. Huseien, G.F.; Ismail, M.; Tahir, M.M.; Mirza, J.; Khalid, N.H.A.; Asaad, M.A.; Husein, A.A.; Sarbini, N.N. Synergism between palm oil fuel ash and slag: Production of environmental-friendly alkali activated mortars with enhanced properties. *Constr. Build. Mater.* **2018**, *170*, 235–244. [\[CrossRef\]](#)
39. Mhaya, A.M.; Algaifi, H.A.; Shahidan, S.; Zuki, S.S.M.; Azmi, M.A.M.; Ibrahim, M.H.W.; Huseien, G.F. Systematic Evaluation of Permeability of Concrete Incorporating Coconut Shell as Replacement of Fine Aggregate. *Materials* **2022**, *15*, 7944. [\[CrossRef\]](#)
40. Tangchirapat, W.; Jaturapitakkul, C.; Chindaprasirt, P. Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Constr. Build. Mater.* **2009**, *23*, 2641–2646. [\[CrossRef\]](#)
41. Abdullah, R.; Wahid, M.B. *World Palm Oil Supply, Demand, Price and Prospects: Focus on Malaysian and Indonesian Palm Oil Industry*; Malaysian Palm Oil Board Press: Petaling Jaya, Malaysia, 2010.
42. Sata, V.; Jaturapitakkul, C.; Kiattikomol, K. Utilization of Palm Oil Fuel Ash in High-Strength Concrete. *J. Mater. Civ. Eng.* **2004**, *16*, 623–628. [\[CrossRef\]](#)
43. Rukzon, S.; Chindaprasirt, P. An experimental investigation of the carbonation of blended portland cement palm oil fuel ash mortar in an indoor environment. *Indoor Built Environ.* **2009**, *18*, 313–318. [\[CrossRef\]](#)
44. Mhaya, A.M.; Baharom, S.; Baghban, M.H.; Nehdi, M.L.; Faridmehr, I.; Huseien, G.F.; Algaifi, H.A.; Ismail, M. Systematic Experimental Assessment of POFA Concrete Incorporating Waste Tire Rubber Aggregate. *Polymers* **2022**, *14*, 2294. [\[CrossRef\]](#)
45. Santhosh, K.G.; Subhani, S.M.; Bahurudeen, A. Recycling of palm oil fuel ash and rice husk ash in the cleaner production of concrete—A review. *J. Clean. Prod.* **2022**, *354*, 131736. [\[CrossRef\]](#)
46. Ali, N.; Sobri, M.H.A.M.; Hadipramana, J.; Samad, A.A.A.; Mohamad, N. Potential Mixture of POFA and SCBA as Cement Replacement in Concrete—A Review. *MATEC Web Conf.* **2017**, *103*, 01006. [\[CrossRef\]](#)
47. Alsubari, B.; Shafigh, P.; Jumaat, M.Z. Utilization of high-volume treated palm oil fuel ash to produce sustainable self-compacting concrete. *J. Clean. Prod.* **2016**, *137*, 982–996. [\[CrossRef\]](#)
48. Hamada, H.M.; Jokhio, G.A.; Yahaya, F.M.; Humada, A.M.; Gul, Y. The present state of the use of palm oil fuel ash (POFA) in concrete. *Constr. Build. Mater.* **2018**, *175*, 26–40. [\[CrossRef\]](#)
49. Ren, F.; Mo, J.; Wang, Q.; Ho, J.C.M. Crumb rubber as partial replacement for fine aggregate in concrete: An overview. *Constr. Build. Mater.* **2022**, *343*, 128049. [\[CrossRef\]](#)
50. Marques, A.; Correia, J.; De Brito, J. Post-fire residual mechanical properties of concrete made with recycled rubber aggregate. *Fire Saf. J.* **2013**, *58*, 49–57. [\[CrossRef\]](#)
51. Al-Mutairi, N.; Al-Rukaibi, F.; Bufarsan, A. Effect of microsilica addition on compressive strength of rubberized concrete at elevated temperatures. *J. Mater. Cycles Waste Manag.* **2010**, *12*, 41–49. [\[CrossRef\]](#)
52. Bravo, M.; de Brito, J. Concrete made with used tyre aggregate: Durability-related performance. *J. Clean. Prod.* **2012**, *25*, 42–50. [\[CrossRef\]](#)
53. Ganjian, E.; Khorami, M.; Maghsoudi, A.A. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr. Build. Mater.* **2009**, *23*, 1828–1836. [\[CrossRef\]](#)
54. Gesoğlu, M.; Güneyisi, E. Permeability properties of self-compacting rubberized concretes. *Constr. Build. Mater.* **2011**, *25*, 3319–3326. [\[CrossRef\]](#)
55. ASTM, C33; Standard Specification for Concrete Aggregates. American Society for Testing and Materials: Philadelphia, PA, USA, 2003.
56. Altwair, N.M.; Johari, M.M.; Hashim, S.F.S. Influence of treated palm oil fuel ash on compressive properties and chloride resistance of engineered cementitious composites. *Mater. Struct.* **2014**, *47*, 667–682. [\[CrossRef\]](#)
57. Baghban, M.H.; Mhaya, A.M.; Faridmehr, I.; Huseien, G.F. Carbonation Depth and Chloride Ion Penetration Properties of Rubberised Concrete Incorporated Ground Blast Furnace Slag. In *Solid State Phenomena*; Trans Tech Publications Ltd.: Bâch, Switzerland, 2022.
58. Ismail, M.; Ismail, M.E.; Muhammad, B. Influence of elevated temperatures on physical and compressive strength properties of concrete containing palm oil fuel ash. *Constr. Build. Mater.* **2011**, *25*, 2358–2364. [\[CrossRef\]](#)

59. Demirel, B.; Keleştemur, O. Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. *Fire Saf. J.* **2010**, *45*, 385–391. [[CrossRef](#)]
60. Neville, A. *Properties of Concrete*, Pearson Education Limited. *Edinb. Gate Harlow Engl.* **2011**, *6*, 58–661.
61. Li, L.-J.; Xie, W.-F.; Liu, F.; Guo, Y.-C.; Deng, J. Fire performance of high-strength concrete reinforced with recycled rubber particles. *Mag. Concr. Res.* **2011**, *63*, 187–195. [[CrossRef](#)]
62. Handoo, S.; Agarwal, S.; Agarwal, S. Physicochemical, mineralogical, and morphological characteristics of concrete exposed to elevated temperatures. *Cem. Concr. Res.* **2002**, *32*, 1009–1018. [[CrossRef](#)]
63. Janotka, I.; Nürnbergerová, T. Effect of temperature on structural quality of the cement paste and high-strength concrete with silica fume. *Nucl. Eng. Des.* **2005**, *235*, 2019–2032. [[CrossRef](#)]
64. Savva, A.; Manita, P.; Sideris, K. Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. *Cem. Concr. Compos.* **2005**, *27*, 239–248. [[CrossRef](#)]
65. Yang, H.; Lin, Y.; Hsiao, C.; Liu, J.-Y. Evaluating residual compressive strength of concrete at elevated temperatures using ultrasonic pulse velocity. *Fire Saf. J.* **2009**, *44*, 121–130. [[CrossRef](#)]
66. Huseien, G.F.; Sam, A.R.M.; Mirza, J.; Tahir, M.M.; Asaad, M.A.; Ismail, M.; Shah, K.W. Waste ceramic powder incorporated alkali activated mortars exposed to elevated Temperatures: Performance evaluation. *Constr. Build. Mater.* **2018**, *187*, 307–317. [[CrossRef](#)]
67. Mohammed, B.S.; Hossain, K.M.A.; Swee, J.T.E.; Wong, G.; Abdullahi, M. Properties of crumb rubber hollow concrete block. *J. Clean. Prod.* **2012**, *23*, 57–67. [[CrossRef](#)]
68. Sukontasukkul, P. Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. *Constr. Build. Mater.* **2009**, *23*, 1084–1092. [[CrossRef](#)]