Post-fire mechanical properties of concrete made with recycled tire rubber as fine aggregate replacement

Muhammad Arf Muhammad[1] - MSc
Wrya Abdulfaraj Abdullah[2] - MSc
Dr. Mohamed Raouf Abdul-Kadir[3] - Professor
[1,2,3] Department of Civil Engineering, College of Engineering, University of Sulaimani

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Abstract

In this study, effects of high blazing temperature with varied time durations on mechanical behavior of normal concrete containing recycled tire rubber as a fine aggregate (RTRFA) have been presented. RTRFA is used as a partial replacement of natural fine aggregate to make rubberized concrete. Generally, concrete used in structural members must satisfy fire resistance requirements in building codes. Therefore, this paper aims at studying the performance of the rubberized concrete prior and after its exposure to fire in accordance with ISO 834 curve for firing. It has been stipulated that the presence of tire rubber particles is mostly for the consideration of environment safeguard. In this investigation, five different concrete mixes were prepared with Ordinary Portland Cement, natural fine and coarse aggregate, with fine aggregate replacement ratios (0%, 6%, 12%, 18% and 24%) by weight. From these mixes, 60 cylindrical specimens (100mm diameter × 200mm high) and 60 cubic specimens (150mm×150mm×150mm) were prepared. These concrete specimens were divided into four groups, consisting of 15 cubes and 15 cylinders each. The first group (so called "control") were tested without exposing it to fire and the remaining three groups were separately subjected to fire for three different time periods vis. (20, 40 and 60 minutes) in a furnace fabricated according to ASTM E119. Then the concrete specimens were tested to observe the post-fire mechanical properties including split tensile strength, compressive strength and ultrasonic pulse velocity. The results of time-temperature curves, slump, fresh density, hardened density, percent-mass loss, compressive strength, split tensile strength of all the mixes are presented. The results showed that both the compressive strength and split tensile strength of concrete mixes decreased with higher percentage replacement of fine aggregate by RTRFA before and after exposure to fire. Moreover, longer time of fire duration or higher replacement ratios leads to further strength reduction of compressive and split tensile strengths. Finally, statistical equations were derived to predict these properties of concrete with RTRFA replacements.

Key Words : Fire, Rubberized concrete, Post-fire Mechanical properties, Recycled Tire Rubber Fine Aggregate (RTRFA).

1. Introduction

Waste tire management has become a considerable issue worldwide recently. An estimated 1000 million tires per year reach end of their life cycles annually (WBCSD, 2010) and the figure has been expected to increase progressively to an annual of 1200 million tires by year 2030 (Pacheco-Torgal, 2012). Landfilling of discarded tires still exist in many countries, i.e. the United States as a method for disposing waste tires. This method negatively influences both health and environment, and it also causes to lose a possible resource.

Concerning civil engineering application, a suitable solution can be the recycling of waste tires as rubber aggregates to replace the fine and coarse aggregates in concrete. There are two forms of rubber aggregates; Chipped and crumbed rubbers. The earliest is coarser so it can be used to replace coarse aggregates and the later one is finer therefore it is widely used to replace fine aggregates in the concrete. A number of studies (Rashad, 2016) have been conducted to investigate the effect of crumb rubber as replacement of fine aggregates in concrete. From mechanical point of view, the majority of researchers have testified that the replacement of sand by tire rubber leads to a decrease in workability, fresh density, split tensile strength compressive strength, flexural strength, modulus of elasticity of concrete, which are the negative side effects. These decreases in mechanical properties attributes mainly to both low mechanical properties of tire rubber aggregates and weak bond between the tire rubber particles and other concrete ingredients. However, some studies have beneficially highlighted that rubberized concrete has less mass, more ductile and more durable in terms of chloride penetration, when compared to the counterpart normal concrete (Rashad, 2016).

Fire is one of the most serious situations to which structures may be exposed. Therefore, concrete members used in structures shall satisfy relevant fire safety requirements detailed in the building codes (ACI 216.1, ACI 318-14, EN 1991-1-2). The fire resistance of concrete structural elements depends on many properties such as mechanical, deformation and thermal. These properties are governed by rate and duration of fire exposure, mix batch and material characteristics (Kodur, 2014). Presence of RTRFA in concrete was the hypothesis to figure out the fire resistance of the rubberized concrete in evaluation with those of the equivalent normal concrete.

Regarding the fire resistance of concrete made with RTRFA, a few studies have been reported in the literature. (Correia et al. (2012) partially replaced natural aggregates in concretes with shredded rubber at levels of 0%, 5%, 10% and 15%, by volume. They reported that higher rubber amount and growing heat flux led to worse fire reaction response mainly in terms of heat release rate, ignition time, and smoke production. Marques et al. (2013) also made concrete mixes with crumb rubber at replacement levels of 0%, 5%, 10% and 15%, by volume. The specimens were exposed to three elevated fire temperatures 400, 600 and 800 °C for 1 hour in accordance with ISO 834 in a controlled fire furnace. Results revealed that the residual compressive strength and residual splitting tensile strength reduced significantly after fire exposure. These decreases in strength rose up with increasing replacement ratios. Moreover, they suggested that the comparative decline of strength in the rubberized concrete should not stop it from being used in structural applications. Liu, et al (2013) have reported the efficient spall prevention of rubber for the concrete when (1%) of sieved rubber particles had been used. Therefore, rubberized concrete has the spalling resistance.

2. Research Significance

Studying the behavior of rubberized concrete exposed to fire is one of the serious concerns related with the use of RTRFA as an ingredient. These concerns are fundamentally originated from the carbon-based and flammable nature of RTRFA and its low degradation burning temperature (Correia, 2012). This paper investigates post-fire mechanical properties of concrete made without and with different partial replacement of fine aggregate by RTRFA. The main development was to evaluate split tensile strength and compressive strength of rubberized concrete subjected to different time durations of fire exposure. For that purpose, five concrete mixes were made: one reference control without RTRFA and four concrete mixes where the fine aggregate masses (6%, 12%, 18% and 24%) were replaced by RTRFA. 120 test specimens (60 cubes and 60 cylinders), divided into four groups, were prepared from the five concrete mixes. The first group was tested without fire and the rest were exposed to three varied time periods (20, 40 and 60 minutes). The purpose was to determine and compare their properties, namely: (i) Slump, (ii) Fresh density, (iii) Mass loss, (iv) Split tensile strength, (v) compressive strength. Based on the experimental results several mathematical equations were proposed to consider percent replacement and estimate the amount of loss in post-fire mechanical properties of the concrete containing RTRFA.

3. Experimental Works

Five concrete mixes were prepared and divided in to two groups of cubic and cylindrical. Each specimens group involved 15 cylinders (with the 100mm diameter×200 mm high) and 15 standard cubes (with dimensions of 150mm×150mm×150mm). In the following sections, basic properties of the essential ingredients used, their mix proportioning, specimen preparation and fire exposures arrangement will be given in details.

3.1. Materials

The cement used in all mixes was Ordinary Portland Cement (Type 1) manufactured locally according to EN 197-1:2011 with a strength of 42.5 MPa. Fine aggregates were naturally obtained from medium river sand with maximum size of 4.75mm, loose dry density of 1322 kg/m^3 and saturated specific gravity of 2.59. Coarse aggregates (max. size =10mm) were also brought from river with saturated specific gravity of 2.64. Recycled tire rubber (max. size=4.75mm) was made by crushing disposed tires in a grinding machine… The tire rubber has a dark color and a compacted dry density of 677 kg/m³. In addition, drinkable water was used. Particle size distributions of both fine and coarse aggregates were according to BS EN 12620:2002, as shown in Figure 1. Furthermore, the sieve analysis of the recycled rubber resulted in its 98% particles passing 4.75mm sieve. Table 1 shows the physical properties of the aggregates and recycled rubber including specific gravity and water absorptions according to (ASTM C127 & C128-98), dense and loose bulk density confirming to (BS 812: 2: 1995).

3.2. Mix Proportioning

Five various mixes with different mix proportions have been prepared to make the specimens. Fine aggregates in Mix 1 was natural without recycled tire rubber whereas in the other four mixes recycled tire rubber were used to partially replace the fine aggregates. The concrete with later mixes is referred to as rubberized concrete in the following context. In the four rubberized concrete mixes, the tire rubber contents were 6%, 12%, 16%, 18% and 24% by weight of the sand. First, the parameters of the concrete components found in material tests were used to design Mix 1 accordance to ACI 211.1. The maximum range of slump (80mm-140mm) was targeted to save adequate workability of other mixes, in case the workability loss might occur with increasing tire rubber. The anticipated mean compressive strength for the concrete mix was 40 MPa. Specific gravities of both fine and coarse aggregates were 2.64 and 2.59, respectively. Consequently, the concrete mixture proportions were 1:1.179:1.345:0.393 by weight for cement, fine aggregate, coarse aggregate and water, respectively. As a reference to the mix proportion, a concrete batch of 0.124m³ was considered for each mix, as summarized in Table 2. The amount of concrete in each batch was increased by 10 % for the planned specimens. The w/c ratio was the same for all five mixes. Furthermore, Weights of cement, water and coarse aggregates were constant in each mix.

3.3. Specimens Preparation

For each mix, the materials were weighted by an electric scale. Then dry ingredients were placed in a steel tray Firstly, aggregates and recycled tire rubber were completely dry mixed together till the tire visually seen thoroughly mixed with the aggregates. After that, the cement is mixed with the aggregates in dry condition, and the water was finally added. The Batching took approximately 10 minute from mixing materials till the fresh concrete appeared to be homogeneous. All molds (cubes and cylinders) were cleaned and oiled then the concrete was placed in two layers. The specimens were cast on a table vibrator and each layer of concrete was compacted for about (5-10) seconds. All the cubes and cylinders for each mix (total 12 cubes and 12 cylinders) were cast in one batch, therefore 3 identical specimens were used for each and all test durations (0, 20, 40, 60 minutes). The specimens were removed from the molds after 24 hours and cured for 28 days in a water tank after which they were taken out from water and then dried in a laboratory at an air temperature of 20 °C before being exposed to fire.

3.4. Tests on Fresh Concrete

Tests on fresh concrete started after completion of mixing. The workability of the different fresh concrete mixes was measured using the slump cone test according to BS EN 12390-2. After the concrete batch mixed consistently manually, the slump cone test was carried out immediately on each mix batch corresponding to percent replacement, as shown in Figure 2. Fresh concrete density of the mixes was also measured by weighing cube specimens just after table vibration. Three cube specimens from each mix were used to find the average fresh density of the same mix.

3.5. Specimens firing procedure

A burning furnace with inside dimensions of (1m long, 0.8m wide and 0.5m high) was constructed in the laboratory as shown in Figure 3. The furnace wall was fabricated with high thermal bricks (8cmX12cmX24cm) size. Two steel plate lids filled with 5cm thick layer of sand were used to cover the furnace top. Two natural fluid gas burners were installed inside the furnace and each one linked to a cylinder bottle with a gas capacity of 12.5 Kg. Two thermocouples were installed at the specimen top surface and another at the fire at bottom of the specimen. Furnace temperatures were observed by three electronic thermometers and a laser thermometer to determine temperature time curves.

Figures 4 to 6 show the temperature-time curves for each burning period. In each chart, four curves are drawn representing different location inside the furnace: The Laser represents the average of four values on side surface of the specimen'. Top and Bottom represents average of four values under and above specimens. In addition to ISO 834 defined time temperature history referred to Eurocode 1—part 1.2 to represent the fire exposure reference as:

$$T_t = 20 + 345 \times \log_{10}(8 \times t - 1)$$

Where T is temperature in (°C) and t is time in minute.
At the end of each burning period, the gas burners were turned off and the two furnace lids were removed from the top of the furnace and then specimens were safely taken out and put on a soft platform of sand in the laboratory till cooling down took place slowly in air .Afterwards, the specimens were taken to perform the mechanical tests.

3.6. Tests on Specimens

The specimens were tested before and after their exposure to fire. The tests included (samples' weights, non-destructive compression test using ultrasonic pulse velocity, compression strength, for cubic samples, and indirect tensile strength. Firstly, masses were recorded before testing using electronic scale of 0.5g accuracy to find the percent of mass loss for each sample after burning. Then they were tested using ultrasonic pulse velocity instrument (E48 from Controls Company, Italy) according to BS EN 12504-4:2004 for the purpose of strength correlation. Additionally, after burning, the weight of the concrete cube samples were taken again then crushed under compression testing machine at a loading rate of 0.6 MPa/sec to find their compressive strength in accordance with BS EN 12390-3:2009. Moreover, the cylindrical specimens were burnt and tested for indirect split tensile strength using the same compression testing machine with a loading rate of 0.06 MPa/sec.

4. Tests Results and Discussions

4.1. Slump

The workability of the different fresh concrete mixes was measured by means of the slump cone test according to BS EN 12390-2. The slump remained approximately constant up to 12% replacement. However, for the remainder of the samples, slump decreased gradually 140, 135, 130, and 110 mm at 6%, 12%, 18% and 24% replacement respectively. Figure 7 shows the results of the slump test for samples with different rubber content. The difference in slump was only due to the changing of mass of the RTRFA as concrete mixes with and without RTRFA had the same w/c ratio. Therefore, it is concluded that mixes with increasing percentage of TRRFA lead to a decrease in slump. Finally, equation 1 (with R^2=0.9747) represents an empirical relationship driven from the observed data.

$$y = -0.0794x^2 + 0.7381x + 139.29 \qquad (1)$$

Where y is slump in mm and x is percent replacement of fine aggregate by weight

4.2. Density

Figure 8 shows the fresh-state density of the concrete mixes with respect to percent tire replacement. A linear decrease can be noted with increasing percentage of fine aggregate by RTRFA. This consisting the difference in dry density of fine aggregate (1600 kg/m3) and RTRFA (577 kg/m3). Fresh density is 2267 kg/m³ for concrete with 0% replacement while this value significantly decreases to 2092 kg/m³ for the concrete mix with the 24% replacement. The following linear equation (R^2 = 0.988) has been proposed to indicate the amount of density in fresh state for rubberized concrete.

$$y = 2263.1 - 7.56x \qquad (2)$$

Where y is fresh density in kg/m³, and x is RTRFA to fine aggregate ratio by weight.
Figure 9 presents the dry density of the various concrete mixes after 28 days with respect to RTRFA content. The results show a decrease in dry density with increasing replacement ratio. Values linearly fall from 2290 kg/m3 for the normal mix to 2100 kg/m3 for the mix containing 24% of RTRFA. An empirical equation (R^2 = 0.9654) is driven from the observation.

$$y = 2300.1e^{-0.003x} \qquad (3)$$

Where y is dry density in kg/m³, and x is RTRFA to fine aggregate ratio by weight.
The reduction in both dry and wet density comparing to reference specimens is attributed to the difference between density of the RTRFA and fine aggregate. From the literature, results confirmed the nonlinearity of the variation in both dry density and fresh density with respect to percentage of replacement, due to the increase in

the level of voids with rubber content (Bravo and Brito, 2012). For instance, the rubber contributes to the mix with the capillarity of its surface, which may grasp higher air entrainment.

4.3. Visual observations of the samples during and after burning

While specimens were inside the furnace, a thick dark smoke rose into the atmosphere indicating burning of the rubber grains at and near the surface of the concrete samples. The specimens with higher ratio of RTRFA produced higher amount of smokes compared to those with lower ratio of RTRFA. Additionally, the smoke increased persistently along with the period of exposure temperature. It was noted that the specimens with 12%, 18% and 24% flashes with fire in the furnace even after removing the lid of the furnace. For example, specimens with 24% replacement flashed with fire and smoke continuously for 15 minutes when exposed to fire for 60 minutes. Signs of explosive spalling had been noted during burning in the specimens of 0% and 6% replacement. Additionally, all specimens exhibited surface cracks of different lengths and widths which increased with increasing periods of fire exposure. Moreover, the surface color of the specimens also experienced considerable changes. For instance, the specimen surface without RTRFA remained bright while the specimens containing RTRFA gained a brown/black color because of the dispersion of black carbon released from RTRFA burned particles. Figure 10 demonstrates an internal view of all types of specimens with different mixes and burning durations after testing for splitting tensile strength. A change in color can be noted for the specimens with no fire from bright white to brown at 24% replacement. The decomposition of RTRFA can be noted in the durations of 40 and 60 minutes. The inside of the specimens of 24% replacement ratio changed into black due to diffusion of the carbon from the RTRFA. It is concluded that the inside color turned into black at higher percent replacement and longer burning period.

4.3. Mass loss

The concrete lost some weight of its hardened state while subjected to fire. Figure 11 and 12 show the results of percent mass losses of both cubes and cylinders for the fire exposure periods (20 minute, 40 minute and 60 minute) with respect to the corresponding percent replacement of RTRFA. With increasing percent replacement, the percent mass losses increases slightly. These increases in percent mass loss are vital with the burning longer periods of 40 and 60 minutes. On the other hand, the durations of fire exposures have caused a gradual mass loss. Specimens exposed to 60 minute fire lost their masses more than those exposed to fire for 20 minutes and 40 minutes. These mass losses belong to the evaporation of entrapped water and burning of the RTRFA particles during fire.

4.4. Compressive strength

Figure 13 shows the results of compressive strength (fcu) for concrete mixes of no fire exposure and three periods of fire exposure corresponding to their percent replacement of RTRFA. This figure clearly shows that the increase of rubber content considerably reduces compressive strength whether exposed to fire or not. Regarding to the normal specimens, with no fire, the compressive strength was nearly 57 MPa at 0% replacement and then decreased to 29 MPa at the 24% percent replacement Indicating 49% reduction in strength.

The figure also indicates that the largest decrease in compressive strength compared to the no firing specimens, is for the 20 minutes firing duration, the decreases in fcu for other durations are not directly proportional. Less reductions is indicated when duration increased to 40 and 60 minutes. Values of fcu for 20 minute of burning declined from 37 MPa to approximately 15 MPa at both 0% and 24% replacement respectively. From the test results three empirical equations are derived to predict the compressive strength with various burning periods as shown in Table 3, where y is fcu in MPa, and x is RTRFA to fine aggregate ratio by weight.

Figure 14 shows the percentage reduction in compressive strength in relation with the compressive strength achieved by their identical specimens without fire. The fcu decreases with burning periods for same percent replacement of rubber. This decrease is attributed to both the physical properties of RTRFA particles and fire exposure: i.e. RTRFA particles are less stiff than the surrounding aggregates and under loading, cracks are initiated around the aggregate particles, which accelerates the failure in the matrix. In fact, the filling of lightweight rubber particles becomes difficult at high content and voids are introduced into the product Marques et al. (2013). Moreover, the reduction in compressive strength is related to air-entrainment as it leads to losing in density. The fire exposure leads to liquefying or dissolving of RTRFA particles therefore longer burning periods cause more disappearance of rubber and water particles. This disappearance leaves voids in the concrete. The more the air-voids ratio, the lighter the specimen will become leading to more reduction in compressive strength.

4.5. Split tensile strength

Figure 15 demonstrates the results of split tensile strength verses percent rubber replacements. The tensile strength of concrete is much lower than compressive strength for the same mix due to propagation of cracks under tensile loads. Split tensile strength of concrete is ranging from 7% to 14% of its compressive strengths. For the specimens without fire, the spilt tensile strength at 0% replacement (4.5 MPa) is lower than that of 6% replacements (6.6 MPa). This may be due to the behavior of the rubber in the vicinity of the cracks in concrete as it might have worked to fill the cracks that formed after applying the loads by bridging the gap as it was formed. From 6% replacement, afterwards split tensile strength declined to 5 MPa, 4.36 MPa, and 3.99 MPa at (12%, 18% and 24%), replacements respectively.
Considering all specimens burnt with their corresponding control specimens, split tensile strengths decreased gradually with increasing periods of fire exposures. The percent reductions in split tensile strength for 20, 40, 60 minutes are shown in Figure 16 with respect to the reference specimens, (No fire). These reductions occur with an increase in both percent replacements and burning periods. The reduction is 10% at 20minutes while it increases to 61% at 60 minutes burning duration. It is concluded that with the increasing of fire duration, the split tensile strength is significantly reduced. For example, specimens burnt for 60 minutes lost greater tensile strength than those burnt for 20 minutes. The causes are the same for the reduction in both split tensile and compressive strength. While the specimens are kept under the flame for a longer period, the RTRFA particles in the concrete are weakened producing new voids inside the concrete and resulting in larger loss of strength. However, the relationship between the decrease in splitting tensile strength and the increase in the replacement rate is not as clear as those for the compressive strength.
Regarding to the relationship of splitting tensile strength (y=ftu) versus percent replacement of RTRFA (x), the equations shown in Table 4 are proposed in order to estimate the split tensile strength at the corresponding exposure periods, as a function of the replacement rate of fine aggregate by RTRFA by weight.

5. Conclusions

In this research, the performance of rubberized concrete (concrete containing RTRFA) subjected to three different firing durations was investigated for post-fire mechanical properties. The experimental investigation resulted in the following conclusions:
RTRFA had a small effect on workability of the concrete in terms of slump at lower rate of 6%. However, slump decreased slightly with the increase in percentage replacement of fine aggregate by RTRFA at greater amount of RTRFA. For instance, slump at 0% replacement was 140 mm and it reduced to 110 mm. at 24% replacement.
Both fresh and dry densities of the concrete decreased with the increase of RTRFA percentage. From 0% to 24% replacement, both fresh and dry density decreased by 175 kg/m^3 and 190 kg/m^3, respectively. The reason of the reduction in both densities may be the differences in the unit weight of RTRFA and the natural fine aggregate.
The rubberized Concrete lost some of its weight with increasing rate of RTRFA. The percent of mass losses became more at longer periods of fire exposures. At 40 minute, percent mass was around 12% while the same specimen lost only 6% for 24% replacement.
Compared to the reference test results, compressive strength reduced with the fire exposure and these reductions gradually continued with different fire period durations. For 0% replacement, fcu reached 57 MPa but it reduced by 55% and 34% at fire exposures of 40minutes and 20 minutes respectively.
Split tensile strength follows similar pattern as compressive strength regarding strength reduction with the increasing fire durations. For example at 40 minute fire exposure, split tensile strength decreased by 48% to 60% for 0% and 24% replacement.
Empirical equations have been proposed based on the test results to estimate the properties of slump, fresh density, dry density, percent mass loss, compressive strength and split tensile strength for concrete containing RTRFA.

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الخصائص الميكانيكية ما بعد التعرض للحرارة العالية للخرسانة المكونة في مطاط الاطارات المعاد استخدامها كبديل للركام الناعم

محمد عارف محمد[1] – ماجستير

وريا عبدالله عبدالفرج[2] – ماجستير

د . محمد رؤوف عبدالقادر[3] – استاذ

[1، 2، 3] قسم الهندسة المدنية –كلية الهندسة – جامعة السليمانية

المستخلص :

في هذا البحث تم دراسة تاثير الحراره العللية عن طريق الحرق لمدد مختلفة علي الخصائص الميكانيكية للخرسانة العادية الحاوية على حبيبات المطاط المعادة استخدامها للاطارات كبديل جزئي للرمل . وتسمي هذا النوع بالخرسانة المطاطية . وحيث ان العناصر الانشائية عليها ان تستوفي جميع متطلبات المقاومة الحرارية حسب المدونات الانشائية . تم اجراء هذا البحث لدراسة الخصائص انف الذكر بعد تعرضها للحريق حسب مواصفات (ISO 834) . تم اختيار خمسه من المزجات الخرساني مكونة من السمنت البورتلاندي والرمل والحصي الطبيعي واستعلمت فيها نسبة وزنيه مختلفة من حبيبات المطاط بديلا عن الرمل وهي (0 ، 6 ، 12 ، 18 ، 24%) من وزن الرمل . ولغرض اجراء الفحوصات المختبرية تم صب (60) مكعبا و (60) اسطونة خرسانية وتم اجراء الفحوص قبل وبعد تعرضها للحريق ولمدد متفاوتة وهي (20 ، 40 ، 60) دقيقة . وقد تم انشاء حجيرة خاصة لاشعال النار للنماذج حسب مواصفات (ASTM E119) . وقد تم دراسة الخصائص التالية : مقاومة الانضغاط ، مقاومة الشد الانفلاق ، قابلية التشغيل ، فقدان الوزن والفحص بطريقة الموجات مافوق الصوتية (UPV) . وقد بينت النتاج بان النماذج تقل مقاومتها عند زيادة نسبـة المطاط البديل للحصي الناعم وكذلك عند زيادة مدة تعرضها للحرارة العالية عند الحرق .

الكلمات المفتاحية : حرق ، خرسانة مطاطية ، خصائص ميكانيكية ما بعد الحرق ، حصي ناعم من مطاط الاطارات المعادة استعمالها .

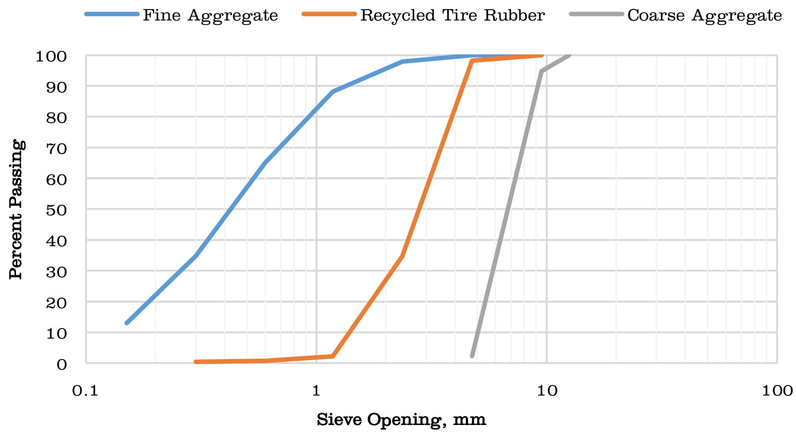

Fig.1: Particle size distribution of aggregates.

Fig.2: slump cone test performance.

Fig.3: The furnace where specimens exposed to fire.

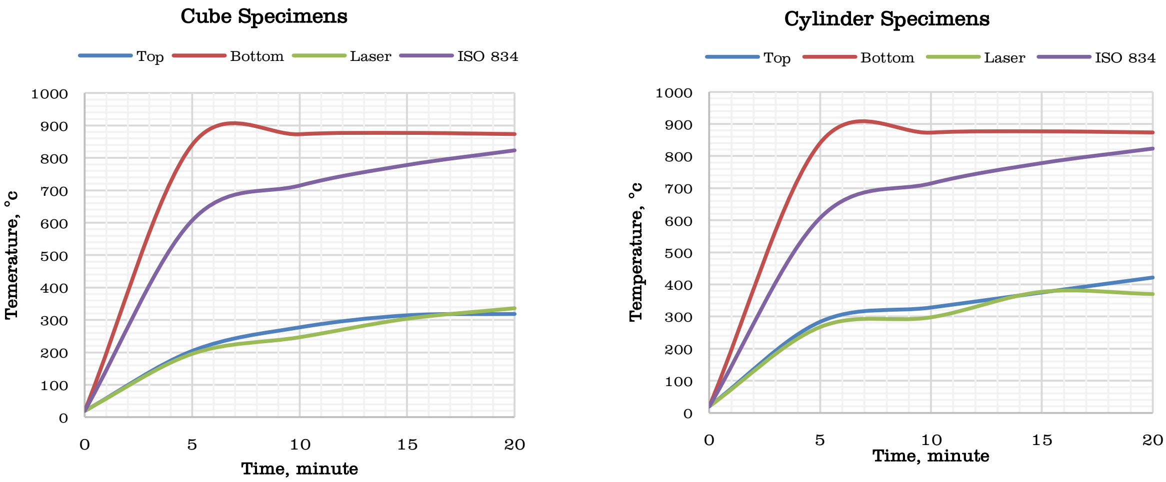

Fig.4: Time-temperature curves for 20 minute period.

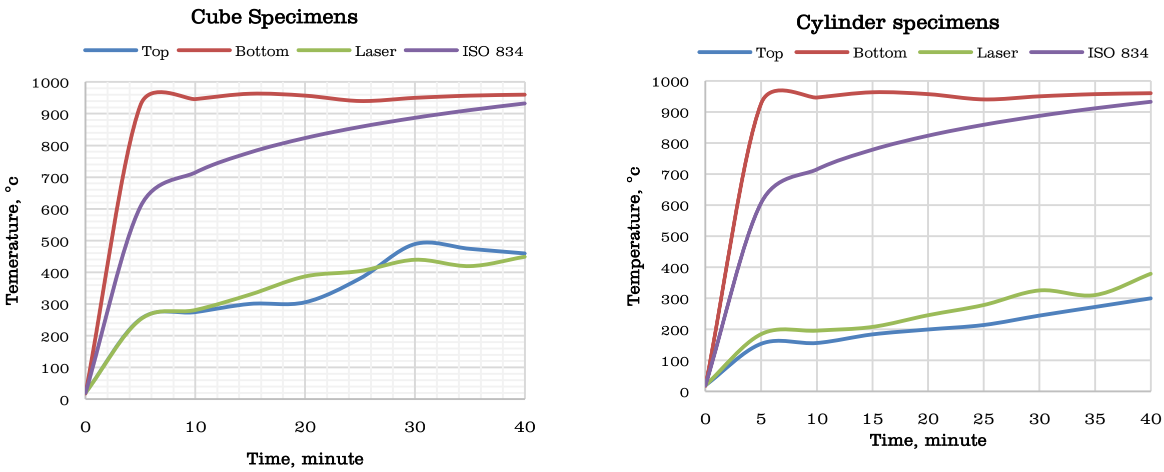

Fig.5: Time-temperature curves for 40 minute period.

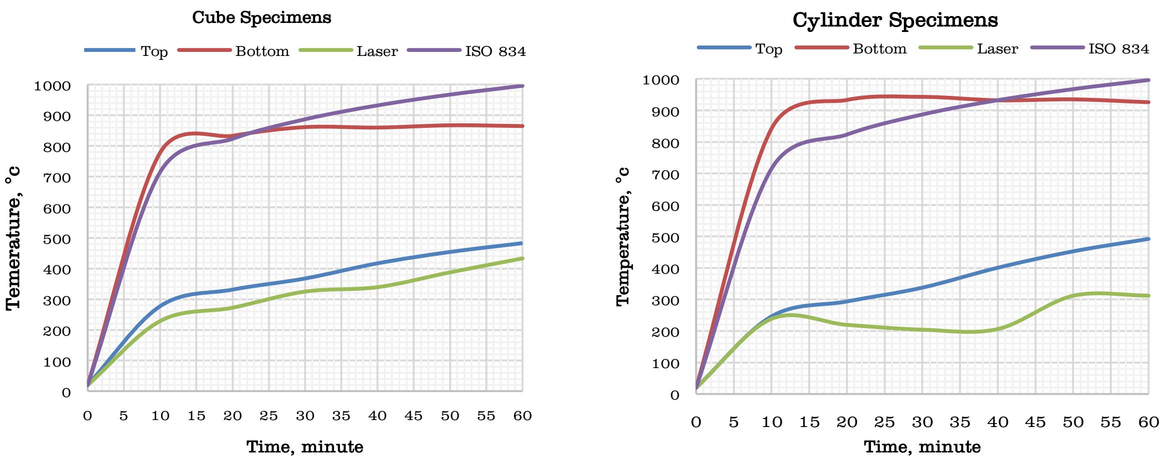

Fig.6: Time-temperature curves for 60 minute period.

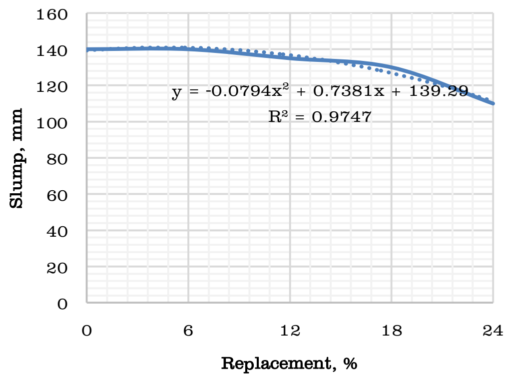

Fig.7: The relationship between the workability of fresh concrete (Slump) and percent replacement of fine aggregate by TRRFA.

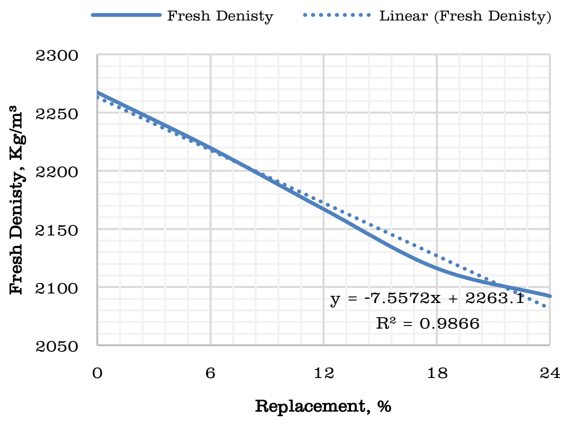

Fig.8: The relationship between fresh concrete density and percent replacement of fine aggregate.

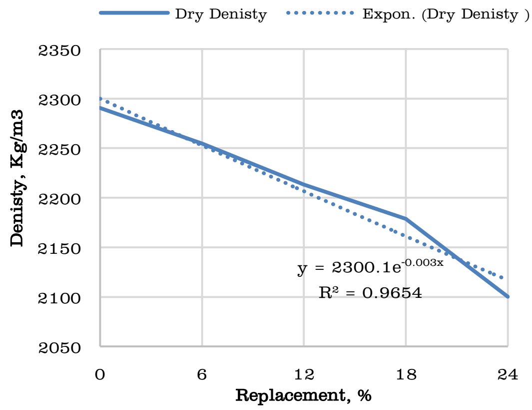

Fig.9: The relationship between hardened concrete density and percent replacement of fine aggregate.

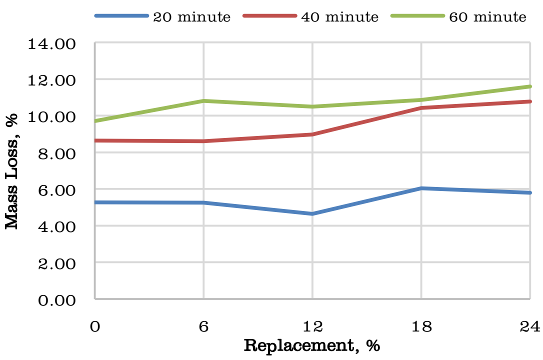

Fig.11: Percent mass loss corresponding to percent replacement (Cubes).

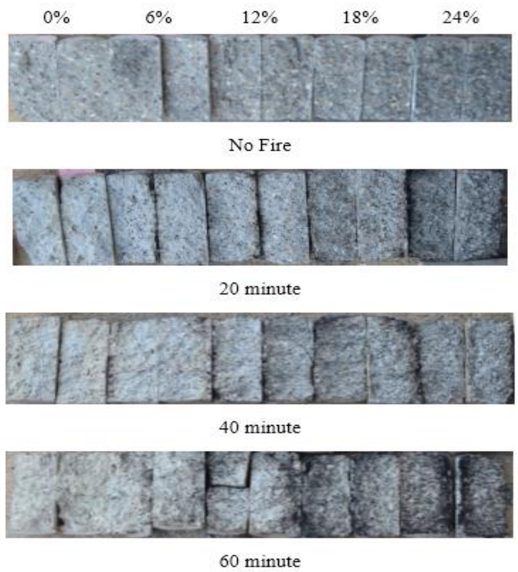

Fig.10: Inside view of some cylindrical specimens after split tensile test.

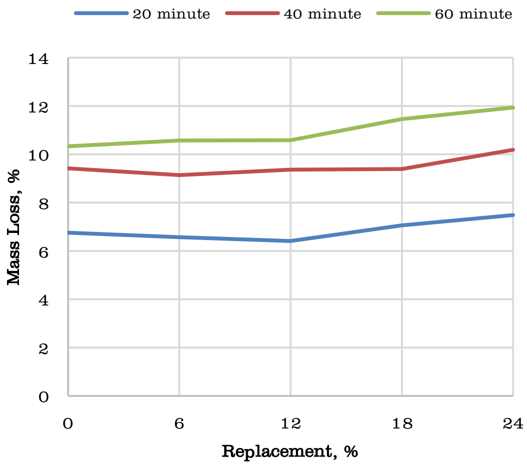

Fig.12: percent mass loss corresponding to percent replacement (Cylinders).

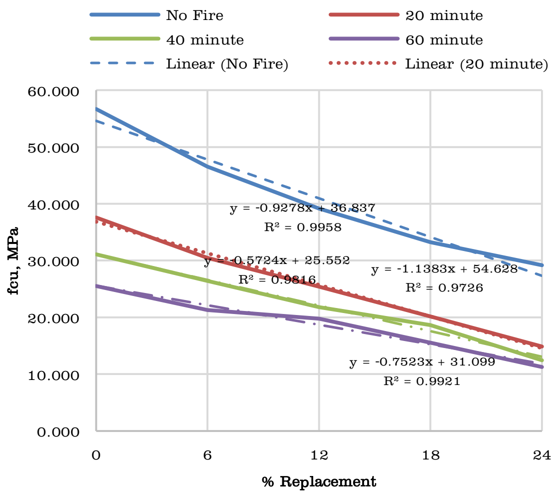

Fig.13: compressive strength verses % replacement for each fire exposure periods.

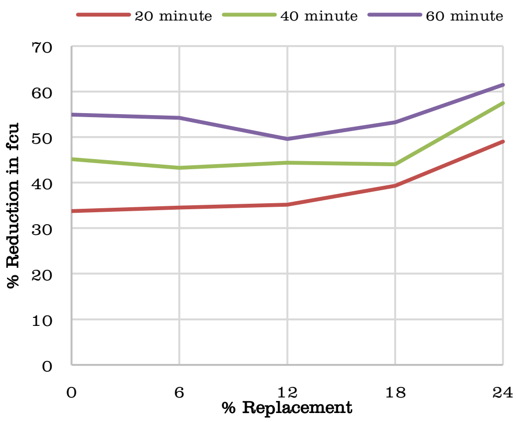

Fig.14: percent reduction in compressive strength.

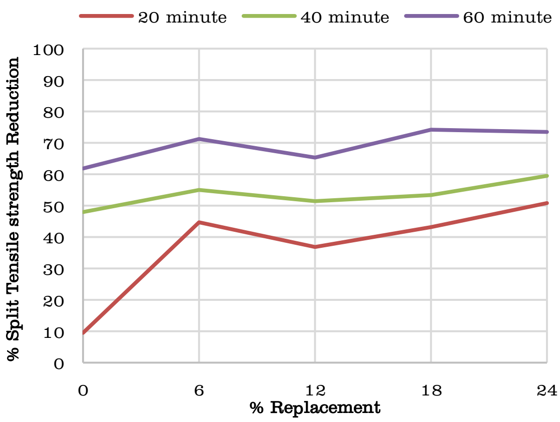

Fig.16: percent reduction in split tensile strength.

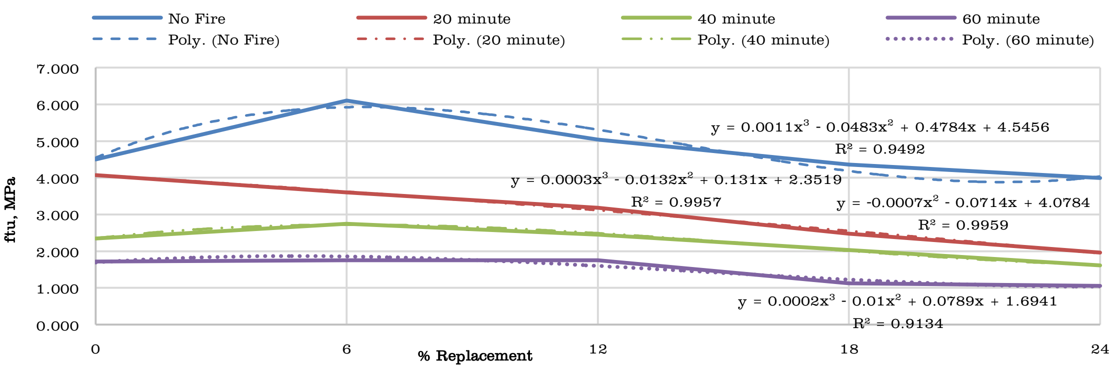

Fig.15: split tensile strength vs % replacement for each fire exposure period.

Table 1: Test results of the aggregates

	Coarse aggregate	Fine aggregate	Tire Rubber
Fineness Modulus, unit less	2.03	2.01	-
Max. particle size, mm	10	4.75	4.75
dense dry density, kg/m³	1679	1552	677
loose dry density, kg/m³	1565	1322	576
water absorption, %	0.96	-	-
the bulk specific gravity, Dry	2.62	2.46	-
the bulk specific gravity, SSD	2.64	2.59	-
the Apparent specific gravity	2.68	2.84	-
Burning point, °C	`		261
Particle surface	Round	-	Round, dry
Source of aggregate	river	river	Tire grinding machine

Table 2: concrete mixture weights of materials used.

Mix ID	Replacement %	Cement, Kg	Fine Aggregate, Kg	Coarse Aggregate, Kg	Water, kg	Tire Rubber, Kg
1	0	84	99	113	33	0
2	6	84	93.06	113	33	5.94
3	12	84	87.12	113	33	11.88
4	18	84	81.18	113	33	17.82
5	24	84	75.24	113	33	23.76

Table 3: Empirical equations of compressive strength for each fire exposure

Fire exposure, minute	R^2	equation
0	0.9958	$y = -0.9278x + 36.837$
20	0.9726	$y = -1.1383x + 54.628$
40	0.9816	$y = -0.5724x + 25.552$
60	0.9921	$y = -0.7523x + 31.099$

Table 4: Empirical equations of split tensile strength for various fire exposure

Fire exposure, minute	R^2	equation
0	0.9492	$y = 0.0011x^3 - 0.0483x^2 + 0.4784x + 4.5456$
20	0.9959	$y = -0.0007x^2 - 0.0714x + 4.0784$
40	0.9957	$y = 0.0003x^3 - 0.0132x^2 + 0.131x + 2.3519$
60	0.9134	$y = 0.0002x^3 - 0.01x^2 + 0.0789x + 1.6941$