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Heat influence on sustainable rubberized concrete mixes

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Abstract

Rubberized concrete (Rubcrete) usually minimizes concrete brittleness and increases conventional concrete's energy absorption as well as the brittleness. Exposing elevated heat deteriorates the strength of traditional concrete and causes rubber dilution. The article investigated replacing aggregate with rubber to enhance the dynamic properties of concrete and discussed many parameters like replacement type, replacement amount, effect of heat and heat increment. Also, many properties, such as unit weight, compressive strength, tensile strength and modulus of rupture, were investigated and discussed for two types of rubber versus aggregate replacement and 10%,20% and 30% percentages. It was concluded that the rubcrete strength was reduced more than the normal concrete due to the presence of rubber, which made the rubber melt inside the concrete pores and caused internal residual stresses due to the hydrostatic pressure. It's not recommended to use rubberized concrete in construction sites exposed to high-temperature rise, like baking ovens or nearby, because the rubberized concrete loses its strength to the fourth or half after exposure to heat.

1. Introduction

Concrete is the most used construction material in the world. It has sufficient mechanical properties to resist static loads but does not meet the requirement for dynamic loading [1–3]. There are many ways to improve the dynamic properties of concrete, such as adding steel fibres, raising its strength with any additives, and using rubber (the best damper between materials) [4, 5]. Using scraped tiers rubbers gets the natural ride of its pollution besides the enhancement to concrete properties, especially after knowing that the pollution in scraped tiers becomes a serious problem against the environment. Because of that, the rubber is a non-biodegradable material and burning it causes effective air pollution[6]. The world produces Millions of tons of tyres per year, about 303 million each year in the United States [6] due to its repeated production and consumption worldwide. The biggest waste tire landfill lies in Arhyyah, Kuwait [7]. It is named Tires' graveyard and can be seen on satellites. Google Maps GPS showed it clearly, as shown in Fig.1. 90% of the recycled tiers rubbers in Mexico are reused in civil engineering applications, and 75% in Canada [8]. It could be used for floor units, walking paths, electricity floor isolation, healthy sports lands, and reinforced dampers for bridges.

Rubber particles produced by recycling factories in many sizes match the grades of sand and gravel particles, so replacing them with the same grades is possible. The factories cleaned the scraped tiers from dust and other unwanted objects and then chopped them for fine and coarse sizes. The fine grades are named crumbs, while the course is called chips, as explained in Fig.2. Effect of heat on rubberized concrete has been investigated previously, and it was concluded that the thermal conductivity of rubcrete is significantly affected by temperature due to porosity changes and water evaporation [9].

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Recycled tiers of rubber could also be used in concrete mixes as a partial replacement for sand, gravel, or even both [9–18], and some researchers used it as a partial replacement for cement. At the same time, other researchers put rubber bars with the primary reinforcement of concrete beams. The replacement may be from the mix volume or maybe from its weight. The volumetric replacement keeps the volume of the mix from changing after replacement. Replacing rubber with aggregate enhances the concrete mix's dynamic properties and makes the concrete absorb more energy and rest many impact loads. But the bad thing is that the concrete compressive strength and the other mechanical properties deteriorate [6, 10–18]. Conventional concrete was tested under heat in many types of research previously, and it was concluded that the concrete keeps the same behaviour in a degree of heat ranging from 65 ℃ to 93 °*c* [19], then it may be changed.

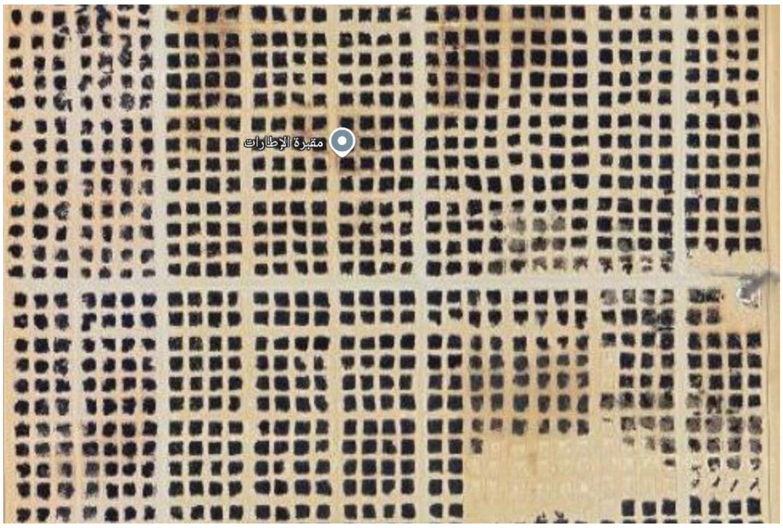


Fig. 1. The most enormous scraped tyres stacks in the world, from Google maps

(a) (b) (c)

Fig. 2. Recycled scraped tyre rubber, which products from recycling factories (a) ground rubber, (b) crumb rubber and (c) chip rubber [9]

The effect of heat on rubberized concrete was investigated in a few articles and in a manner different from this article, in which the researchers applied heat on the rubber before using it in the concrete mix [20, 21], or some papers studied the thermal conductivity of the rubberized concrete [1, 21–24]. This article discusses the effect of heat on the properties of rubcrete after drying and curing; in other words, studying the impact of heat when a fire occurs besides rubberized concrete. As the previous research has approved, conventional concrete loses its strength at a temperature starting from 38 ℃ [28], and the degree of strength dropping has a lower and upper bound limit, depending on the chart. At a temperature equal to 21 ℃ , the dropping in strength equals zero for both upper and lower bounds limits for both compressive and tensile strengths [19].

Abdelrahman Swilam et al. [20] and Osama Youssef et al. [25] investigated the effect of treating the rubber with heat before casting. It was concluded that, compressive strength recovery of 74% and impact resistance enhancements of 2.2 times at the first crack and 92% at the ultimate failure when using rubber content of 40%. The microstructural analyses showed that rubber heat pre-treatment burnt out most of the unwanted materials in rubber aggregate, creating an outer hard shell on the rubber particles [25]. Heating the rubberized concrete after casting and curing has not been investigated yet. So, this study initially discussed the effect of heating the rubberized concrete after curing.

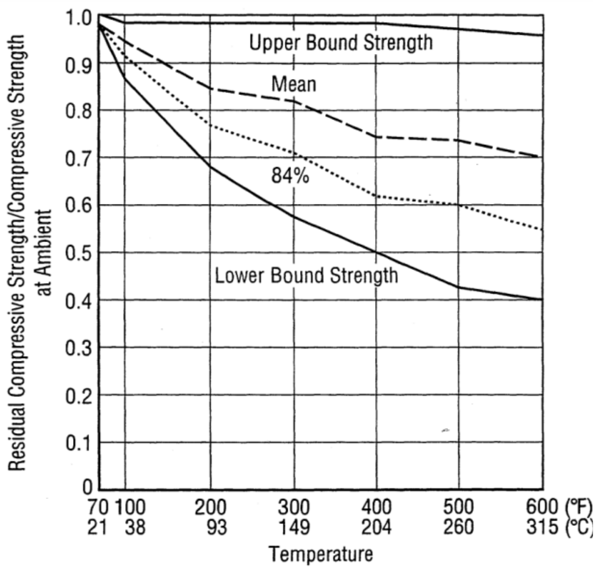


Fig. 3. Lower and upper limits in decreasing the concrete compressive strength after heat [19]

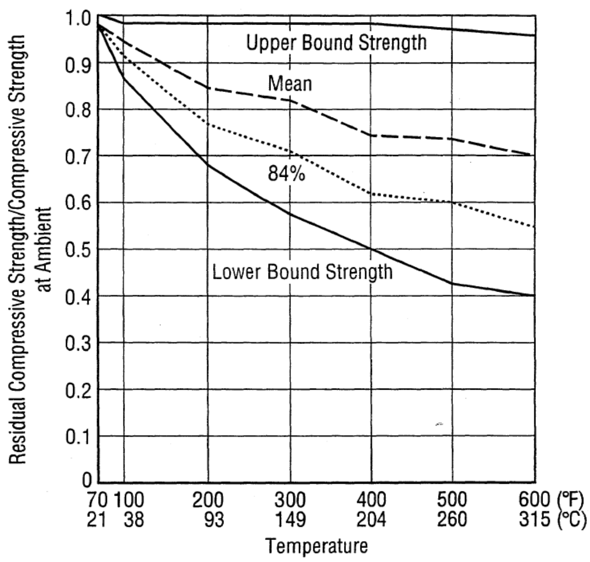
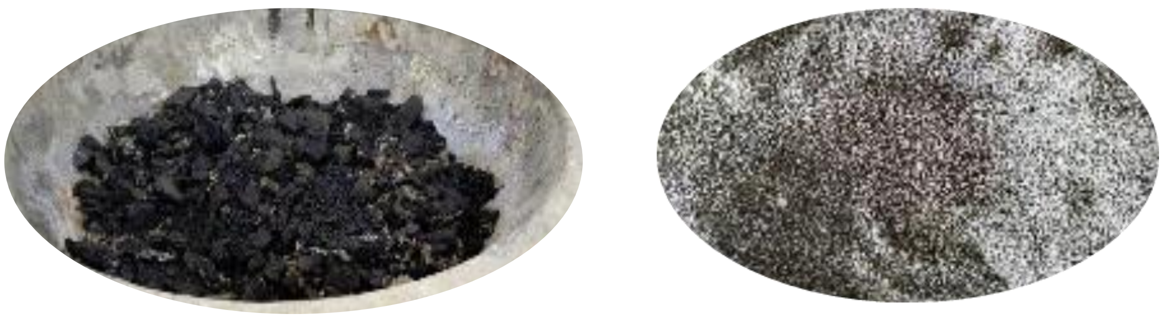


Fig. 4. Tensile strength decrement after elevated heat [19]

2. Test Methodology

Replacing the aggregate with rubber, even if it was totally or partially replaced, led to the introducing of a new material called rubcrete (rubberized concrete). Regular Portland cement was used, a well-graded aggregate and the used rubber was graded in the same gradient. Chips rubber (which partially replaced gravel) was 650 kg/m3, the crumb density was 720 kg/m3, and carbon black equals 20%. The maximum gravel and rubber aggregate size was 10 mm, and passing from 4.75 mm sieve for fine aggregate. The gravel density was 1650 kg/$m^{3,}$ and the sand was 1600 kg/m^3. The cement used was Cement-Basian type, with a mortar compressive strength of 33 MPa for water-to-cement ratio (w/c) equals 0.25. Fig.5. showed the rubber used.



(a) (b)

Fig. 5. Rubber used in mix casting (a) chips rubber, (b) crumb rubber

The study investigated the mechanical and dynamic properties of rubcrete under heat, such as density, water absorption, compressive strength, tensile strength, bending capacity, and impact resistance. All the tests were investigated after 28 days of curing, and all the values were based on the average of three specimens. A slump test for all mixes was made using a 300 mm high coneshaped trunk, as explained in Fig.6.a. The base is 200 mm (8 in) in diameter and has a smaller opening at 100 mm. Each layer is tempered 25 times with a standard 16 mm.

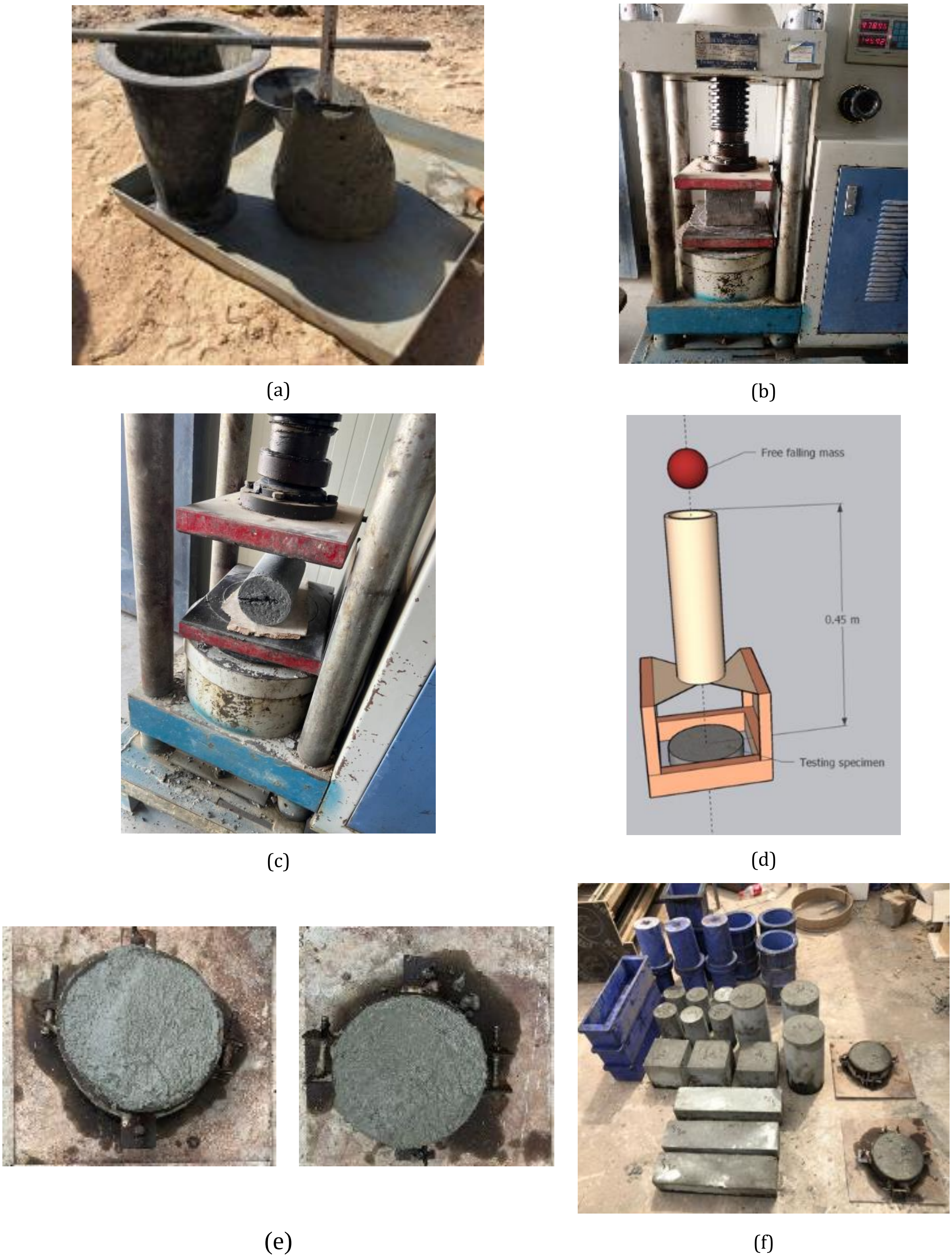


Fig. 6. Represent experimental work (a) Slump test, (b) Compressive strength machine, (c)Splitting strength, (d) Impact load device sketch, € casted impact load specimens and (f) dry samples

The same compressive machine press system was used to test the compressive strength of cubes and the cylinders' splitting. The cubes are inserted into the machine on a face perpendicular to the

casting direction with a loading rate equal to 0.2 MPa/sec, as explained in Fig.6.b. and c. Fig.6.d Explained the testing method, while Fig.6.e illustrated mould casting. Some samples after casting are illustrated in Fig. 6.f.
Following ACI committee 544 [26], the impact resistance of concrete may be obtained by casting cylindrical specimens of 65*152 mm (diameter * length) and applying a drop mass (m) simulated of 4.54 Kg. The number of hits that caused the first crack (N1) and the total number of hits that caused the final failure (N2) were recorded. The total energy applied to the specimen could be calculated from the following equations:

$$\text{energy at first crack} = N_1 mgh \tag{1}$$

$$\text{the energy at failure} = N_2 mgh \tag{2}$$

3. Experimental Mix Preparation

Seven mixes were cast, three of them of sand replacement, the other three of gravel replacement, and one conventional concrete without any replacement. Based on several trial mixes, the mix was of (1:1.4:2) percentages, which means that, for each quantity of cement, the sand amount equals 1.4 multiplied by cement quantity, and gravel equals twice the quantity of cement. The water-to-cement ratio was equal to 0.365. Superplasticizer Gelimum G54 was also utilized. Mix details for one cubic meter are illustrated in Table 1. Note that the names of specimens started with Gr for gravel replacement and Sr for sand replacement, followed by the volumetric percentage of replacement, which is 10, 20 or 30%.

The exact mix investigated in reference [15, 27] was used, so the study concentrated on the prisms' bending capacity after heating, slump test, unit weight after heat, water absorption, and concrete cube's compressive strength. The investigated heat applied on specimens was selected to be 100 °C and 200 °C for two hours.

Table 1. Mixes weights (kg/m^3) [15, 29]

Mix	Cement	Sand	Gravel	Rubber	water	G54
RF	475	760	1119	0	124	2.33
Sr10	475	684	1119	76	124	2.33
Sr20	475	608	1119	152	124	2.33
Sr30	475	532	1119	228	124	2.33
Gr10	475	760	1008	111	124	2.33
Gr20	475	760	896	223.8	124	2.33
Gr30	475	760	784	335	124	2.33

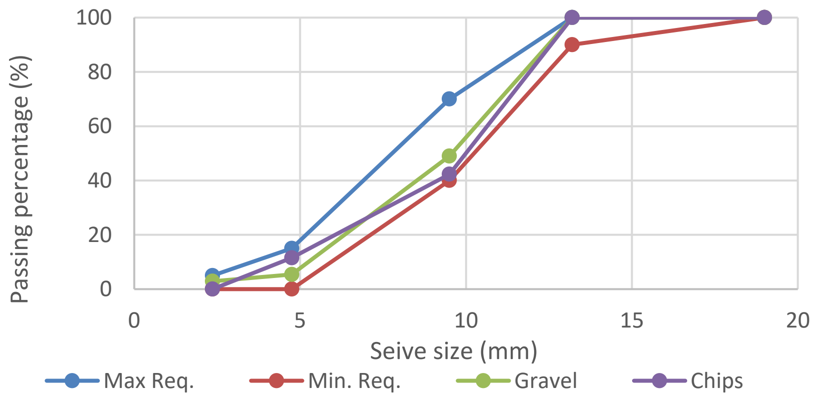


Fig. 7. Gradient of coarse aggregate and chip sizes

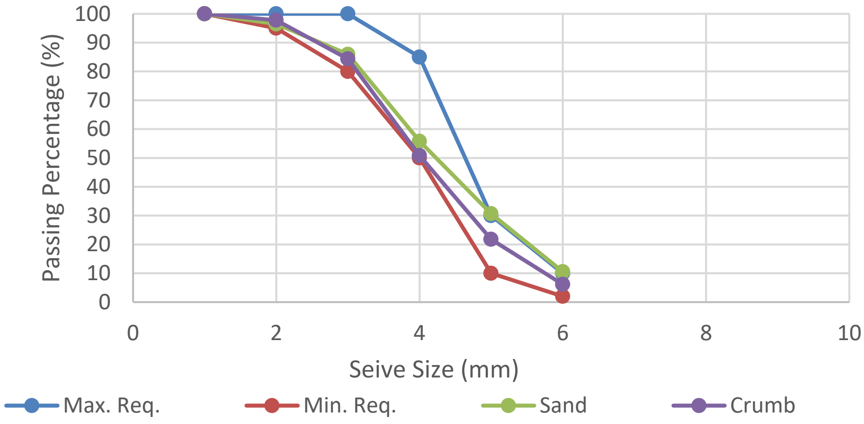


Fig. 8. Sieve analysis for fine aggregates

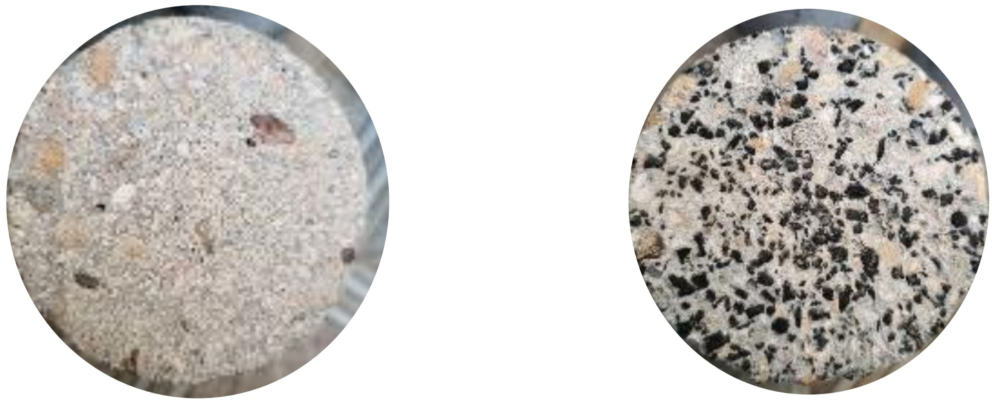


Fig. 9. Conventional versus rubberized concrete face

The dry content is mixed till get a homogenous dry mixture. It was noted that, despite the dark concrete dry mix colour, the fresh rubcrete mix appears darker than traditional concrete due to the presence of rubber. It's recommended by the previous research that, when replacing, it prefers to replace a thoroughly graded rubber with the same fully graded aggregate to avoid a massive loss in concrete strength [6]. So, sieve analysis for all materials was investigated. The gradients of gravel, chips, sand and crumb were used, matching with the maximum and minimum requirement of the recommended sieve analysis provided by ASTM C33-10 [28]; all results were shown in Fig.7 and Fig.8. Fig.9 showed the surface of rubberized concrete of 30% chips content.

4. Rubcrete Properties Result After Heating

4.1. Slump Test

Generally, after reviewing many studies, it was observed that the replacements deteriorate the workability of the mix for various reasons. Since the rubber particles have a hydrophobic surface, water particles do not stick on, contrary to aggregate particles with an absorption capacity [30]. Emam [31] investigated the fact that water covers rubber particles, decreasing the friction between concrete mixes. The fresh rubberized concrete mix flow matches the results at reference [15] because it is the same mix, but slight differences could be noted due to the weather conditions. It can be concluded that the presence of rubber reduces the workability of concrete in magnitudes increases with replacement percentages increment as explained in Table 2, which tested by the ASTM 143M-12 [32]. It also could be noted that the acceptable aggregate replacement is more workable than the coarse aggregate replacement because the chip rubber has many angles that can restrict the water between its particles.

Table 2. Workability results for conventional and rubberized mixes

Specimens	Slump (mm)	Reduction %
NC	105	------
Sr10	92.5	11.9
Sr20	80	23.81
Sr30	65	38.1
Gr10	67	36.19
Gr20	46	56.19
Gr30	37	64.76

4.2. Unit Weight

Replacement generally was proved by the previous research to minimize the unit weight of concrete due to replacing the heavier material (aggregate) with a lighter material (rubber), and this reduction depends on many factors, which are replacement method, the amount of replacement and replacing. In other words, the reduction in unit weight is a result of less rubber density than aggregate, where the density of sand (1450 kg/m3), gravel (1650 kg/m3), and natural rubber (500 kg/m3). After applying heat to the concrete cubes, three cubes from each mix were weighed before and after using heat of 100 °C for two hours. The results (which are shown in Fig.10) introduce that, the weight of rubberized concrete reduces more after heating due to the evaporation of free water from the cubes. Sand replacement specimens lost (1.28% to 1.95 %) of their weight after 100 C of heating and lost (1.8% to 2.98%). Gravel versus chips replacement weight was reduced by (0.74% to 0.97%) after heating for 100 C, while for 200 C of heat, the reduction ranged from (1.5% to 2.77%) according to rubber amounts. Whatever the heat was, and the amount of replacement occurred, the reduction in weight due to heat is so slight and does not reach 5%.

4.3. Water Absorption

Exposing heat to specimens working on emptying the concrete voids from water could cause the voids to receive more water. It was concluded previously from the literature that [6] the water absorption capacity of rubcrete enhanced when increasing the rubber amount; the same behaviour was observed for the heated specimens but with more significant absorption because its voids were dried by heat from free water.

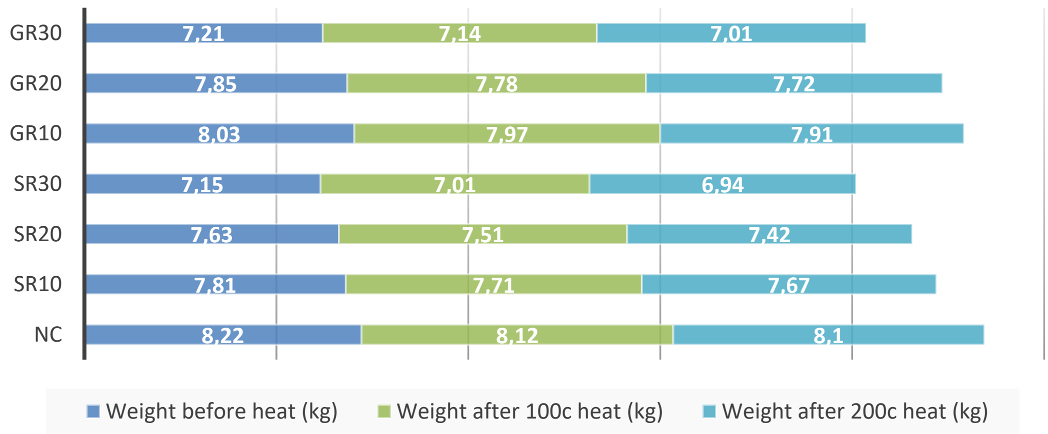


Fig. 10. Weight loss before and after heating

Three cubes from each mix were tested to show the water absorption, and it was concluded from the results listed in Fig. 11 that the water absorption rises gradually after any heat increment; also, it can be noted that the increment reached 8% for 30% sand versus crumb replacement and 8.5% for 30% gravel-chips replacement at 100 C°. At 200 C°, the increment reaches 6.7% and 8.5% for the 30% replacement of sand and aggregate, respectively. The water absorption increases after heat due to evaporating free water mix from pores after heating, emptying the mix cavities and increasing the ability for absorbance.

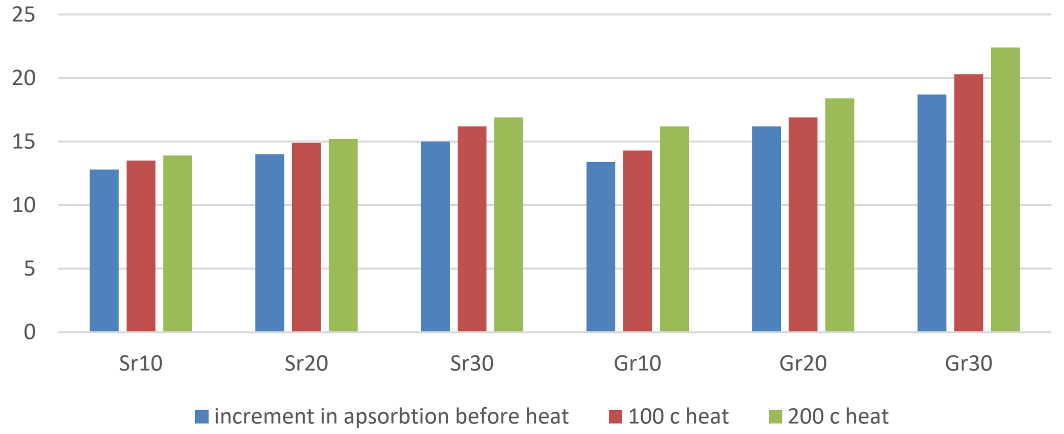


Fig. 11. Water absorption before and after heating

4.4. Concrete compressive strength

The average of three cubes by BS 1881 -116 [33] to get the British compressive strength Fcu. The drop in concrete compressive strength after a replacement was proved by many previous types of research. It was indicated that this drop happened due to forming micro-cracks between the cement paste and the rubber particles (considered an intruder material on the mix) [6]. The same drop observed previously from literature has been noticed in this study, and the decrement amount depends on replacing type and amounts. After heating, the concrete compressive strength also reduces capacity due to factors relenting on concrete and rubber.

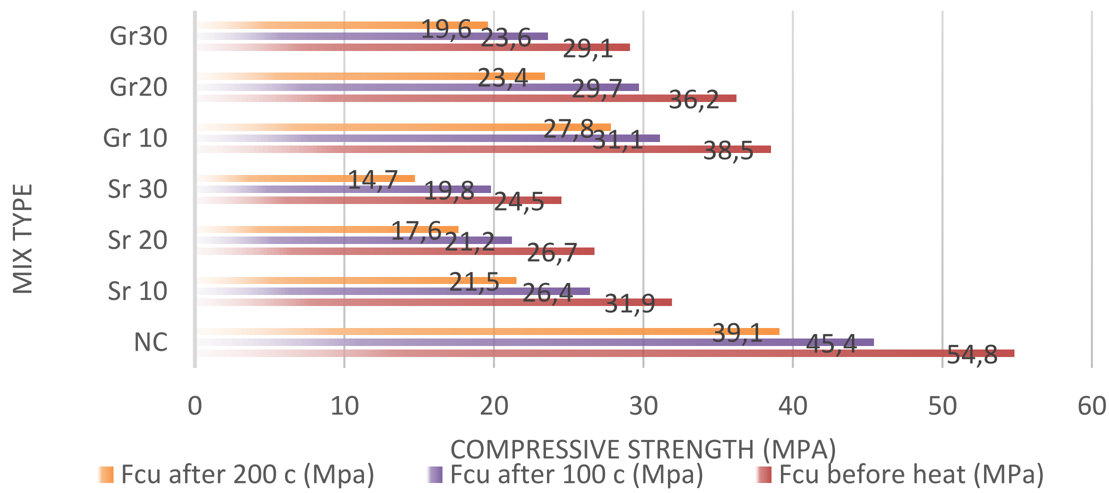


Fig. 12. Concrete compressive strength results

After exposing heat to concrete cubes, a drop in compressive strength was expected for both conventional and rubberized concrete. As could be concluded from the results listed in Fig.12, the traditional concrete strength drops after heating in the range of expectation introduced by the reference [19]. The expected degree of reduction for 100 ℃ and 200 ℃ of heat are (0.87-0.68) and (0.96-0.85), respectively, for lower- upper bounds. When the concrete strength was 54.8 MPa without heating, it is expected (by the chart) to drop the strength in the range between (41.03 MPa to 50.496 MPa) for 100 c and (35.76 MPa to 44.71 MPa) for 200 C, while experimentally it was 45.4 MPa and 39.1 MPa for 100 C and 200 C respectively. The specimen results showed a matching percentage drop compared to the previous articles [19].

For rubcrete material, the decrement accedes 0.84, and it deteriorates more than the conventional concrete. The philosophy of rubcrete reduction could be as follows: the rubber particles start to soften or maybe melt and form some gases inside the concrete, which cause a hydrostatic pressure inside the cube, and a residual pressure will develop inside the concrete block. The results could also be concluded that the sand replacement specimens suffer more heat than the gravel replacement due to the finer size of crumb particles, which made it melt faster than the chips' particles. Fig.13 shows some of the tested specimens after failure.

Fig. 13. Compressive strength failure for some specimens

4.5. Splitting Strength

As usual, splitting strength depends on the concrete compressive strength at the first degree. So, it's logically expected to be dropped after replacement and heating. After heating the specimens (three cylinders from each mix- of 200mm length and 100 mm diameter) in accordance with ASTM VC39/C39M – 15a [34] specification and testing them directly the results were obtained. It could be noted from the results (which listed in Table 3) that, the dropping in strength after replacement ranged from 20% to 47% for acceptable aggregate replacement and 16% to 40.75% for coarse aggregate replacements. After heating under 100 C, the reduction rises by 24% to 52% for crumb specimens and 21% to 48% for chip replacements. At the same time, the reduction in strength gets worse after 200 C° of heating. The decrease in splitting strength comes from the weakness of rubberized concrete due to heating; conventional concrete is affected negatively by heat and rubber, so the decrement occurred from both the weakening and rubber dilution.

It can also be noted that, when comparing sand and aggregate replacements, the gravel replacement introduced a deterioration in strength better than the sand samples, which means that the chips replacement is safer for strength than a crumb. Specimens after failure are shown in Table 3. Fig.14 viewed cylinder failures, which were typically repeated for all specimens.

Table 3. Tensile strength of concrete after and before heating

Mix	Ft (MPa)	Redaction (%)	Ft (MPa) after 100 c	reduction (%)	Ft (MPa) after 200 c	Reduction (%)
Nc	5.12	-----	4.67	-----	3.91	-----
Sr10	4.21	20.21	3.54	24.19	2.67	31.71
Sr20	3.78	35.03	2.98	36.18	2.31	40.92
Sr30	2.95	47.25	2.24	52.03	1.65	57.80
Gr10	4.61	16.12	3.67	21.41	2.84	27.36
Gr20	3.67	32.33	3.04	34.90	2.45	37.34
Gr30	3.21	40.75	2.41	48.39	1.88	51.91

(a) (b) (c)

Fig. 14. (a) Typical shape of cylinder failure. (b) Splitting face of Sr.10 sample. (C) failure face of SR.30 specimen

4.6 Modulus of Rupture

Prisms of (100*100*400 mm) dimensions were cast for the seven mixes to test the modulus of rupture at 28 days according to the ASTM C133-97 [35]. The tested specimens' results were clarified in Fig.15, and accordingly, the rupture strength of rubcrete was reduced due to the reduction in concrete compressive and tensile strength. Results show that the flexural strengths of sand replacement are slightly higher than gravel replacement because sand provides higher ductility than gravel. Rupture test for rubcrete was also investigated widely at reference [36]. For heating results, it can be quickly clarified that the flexural strength of rubcrete prisms deteriorates after the effect of heat in a magnitude depending on the temperature applied. Sand versus crumb specimens lost (17.6-29%) of the flexural capacity, while the chips versus gravel replacement lost (17.2-22%) of the bending capacity after 200 C of heat application. Applying heat on prisms worked on deteriorating the strength of concrete and rubber, which caused the dropping in rupture strength.

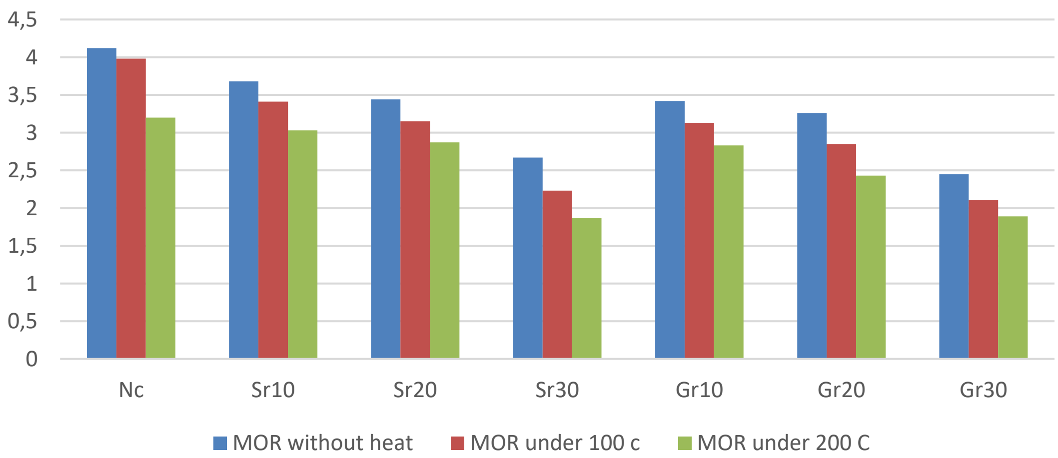


Fig. 15. Modulus of rupture results (MPa)

Fig.16. illustrated the rubberized specimens after failure and before heating; during the test, it was observed that the gravel particles worked as fibres matched between the cracked sides of the prism till completely cutting for the model by the load.

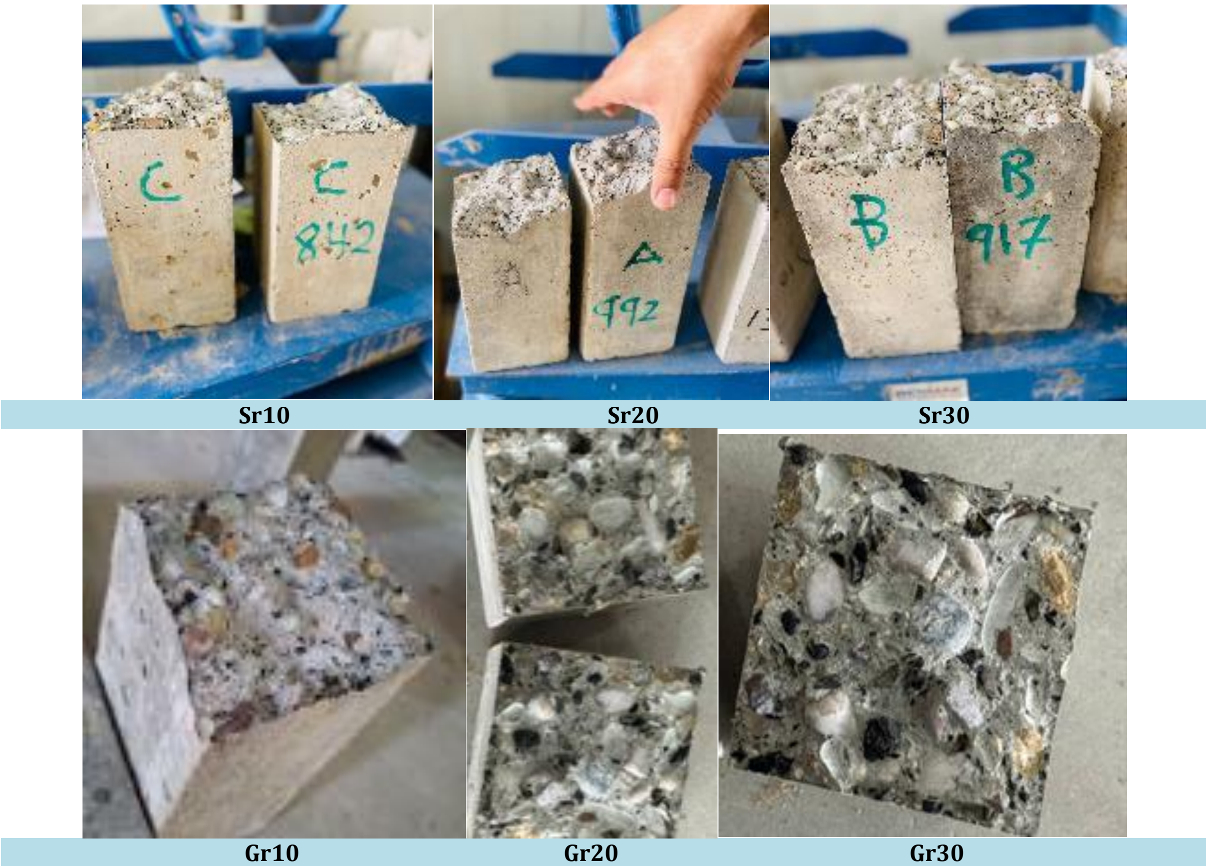


Fig. 16. Rubberized prisms after failure

Fig. 17 illustrates the modulus of rupture (MOR) decrement for the different mixes. Mathematical equations for the decrement in rupture strengths have been discussed. After investigating the best fitting curve, a polynomial from the second degree presented the results accurately for all samples but approaches to be linear at chips versus gravel replacement at 200 C; the equations are shown in Table 4. The reliability factor of the equations equals 1, which means that the equation precisely fits with the results and without error percentage as explained in Table 4.

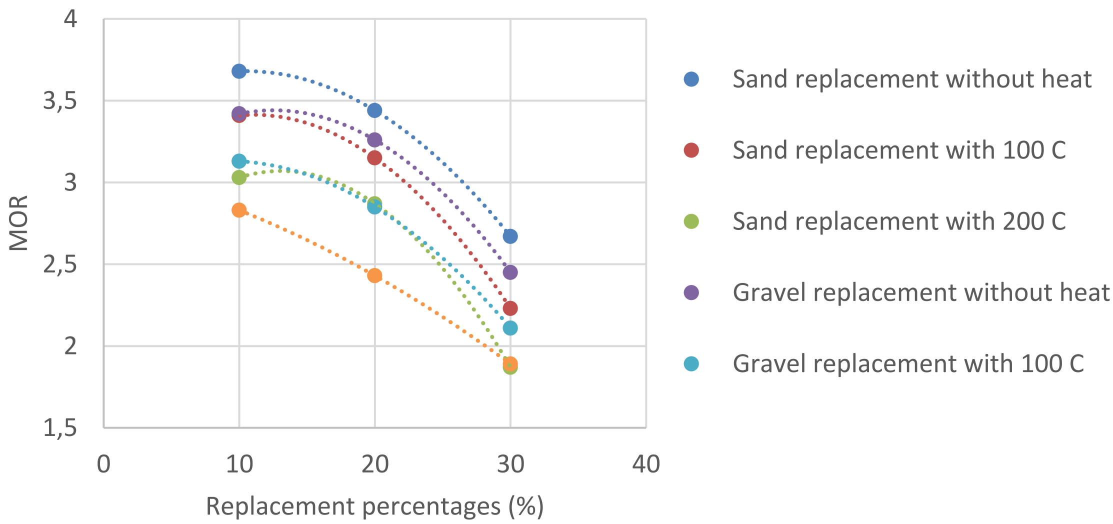


Fig. 17. Decrement in MOR and the suitable equation for the dropping

Table 4. Mathematical model of modulus of rupture for rubberized concrete

Specimen	Equation	Reliability factor
Gravel replacement without heat	y = -0.0032x2 + 0.0815x + 2.93	R2=1
Gravel replacement with 100 C	y = -0.0023x2 + 0.041x + 2.95	R2=1
Gravel replacement with 200 C	y = -0.0007x2 - 0.019x + 3.09	R2=1
Sand replacement without heat	y = -0.0027x2 + 0.0555x + 3.39	R2=1
Sand replacement with 200 C	y = -0.0033x2 + 0.073x + 3.01	R2=1
Sand replacement with 200 C	y = -0.0042x2 + 0.11x + 2.35	R2=1

4.7. Impact load

Adding rubber into the conventional concrete mix dynamically works as micro springs fixed inside the concrete particles, and applying heat melts the rubber and destroys these springs. The results showed that rubberized specimens lose their impact resistance capacity and suffer from weaker absorbing energy. That was concluded from Table 5, which illustrated the capacity of heated and unheated rubcrete under impact loads per the ASTM C496 specifications [37]. The worst matter is that melting rubber minimizes concrete's compressive strength, which also decreases the impact strength of rubberized concrete. From the results, it could be noted that the sand versus crumb replacement specimens lost an impact capacity ranging from 54% to 88% at heat 100 C° and 65% to 92% for heat equals 200 C° which is due to melting the rubber particles and returning the rubberized concrete behaviour to the conventional concrete behaviour. 64% to 84% was the reduction in impact resistance after 100 C of heat subjected to gravel versus chips replacement; for 200 C°, the deterioration in energy absorption was 74% to 88%.

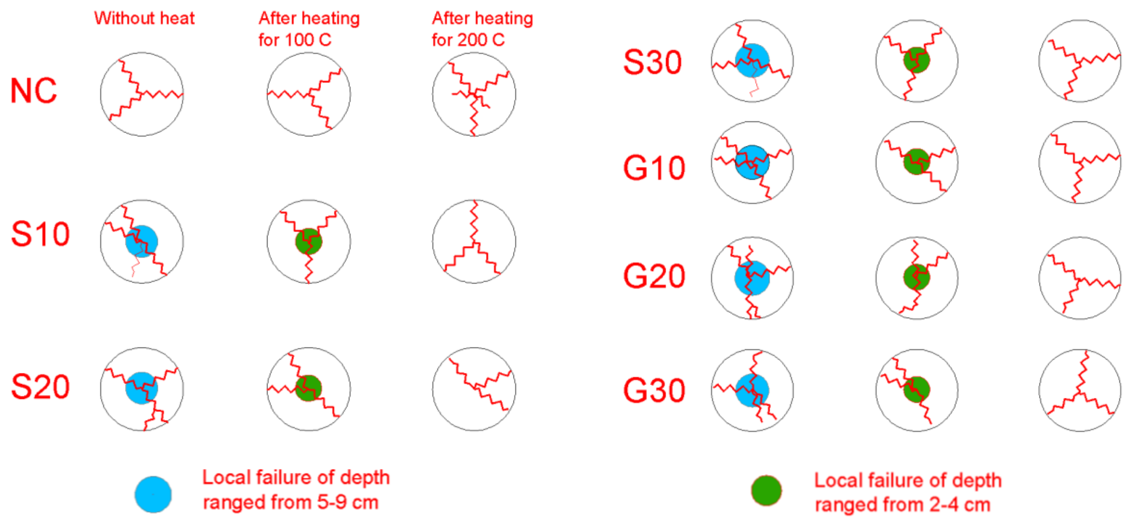


Fig. 18. Failure modes of different impacted specimens

Fig.18 illustrates the crack patterns for all impacted specimens. It can be noted that, before heating, the conventional concrete did not suffer from local failure in contrast to rubber specimens, which showed local failures ranging from 5 mm to 9 mm in depth. The local failure occurs due to rubber particles working on fending off the hit to crack the concrete; after each impact, a small local failure occurs and is cumulative till the final cracking failure happens. The local failure depth decreases for heated specimens at 100 C due to the melting of some rubber particles. In contrast, at 200 C° of heat, the crashing failure does not appear, and the specimen backs to the conventional concrete behaviour because the rubber lost its impact resistance property after melting.

Table 5. Impact resistance values

Specimen	The impact energy of the sample before the heat	Impact energy after 100 C° of heat	Impact energy after 200 C° of heat	Reduction percentage due to 100 C° heat	Reduction percentage due to 200 C° heat
NC	171.2	170.3	169.5	0.52	0.99
Sr 10	352.3	161.4	120.1	54.18	65.9
Sr 20	720.5	155.2	105.8	78.45	85.3
Sr 30	1285.2	142.8	98.7	88.88	92.3
Gr 10	493.6	175.3	125.6	64.48	74.5
Gr20	785.2	167.3	112.3	78.6	85.6
Gr30	2403.7	135.2	101.7	84.8	88.6

5. Conclusions

The effect of heat on rubberized concrete has been investigated using many parameters, such as replacement type, replacement percentages, heat effect, and heat increment. After testing the specimens, it could be concluded the following:

- Rubcrete compressive strength, in general, deteriorates after heat. Rubber particles start to soften or may be melting and form some gases inside concrete which what cause a hydrostatic pressure inside the cube and residual pressure inside the concrete block.
- Sand replacement specimens suffered from heat more than gravel replacement due to the finer size of crumb particles, which made them melt faster than the chip particles. This led to the conclusion that chip replacement is better than crumb replacement for structural members exposed to temperature.
- Dropping in tensile strength after replacement and without heating ranged from 20% to 47% for acceptable aggregate replacement and 16% to 40.75% for coarse aggregate replacements.
- At 100 c, the reduction in tensile strength ranged from 24% to 52% for crumb specimens and 21% to 48% for chip replacements. While the decrease in strength gets worse after 200 C° of heating
- The same behaviour, which appears in compressive strength, appears again in tensile strength; the chip replacement shows more resistance against heat than the crumb samples.
- The sand versus crumb replacement specimens lost an impact capacity ranging from 54% to 88% at heat 100 C° and 65% to 92% for heat equals 200 C°, which is due to melting the rubber particles and returning the rubberized concrete behaviour to the conventional concrete behaviour. 64% to 84% was the reduction in impact resistance after 100 C of heat subjected to gravel versus chips replacement; for 200 C°, the deterioration in energy absorption was 74% to 88%.
- It's not recommended to use rubberized concrete in construction sites exposed to a high temperature rise like baking ovens or nearby because the rubberized concrete loses its strength to the fourth or half after exposure to heat.

The suggested work after such a manuscript is to investigate enhancing rubberized concrete strength to avoid significant loss in strength after heat.

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