CHAPTER 5

TEST RESULTS OF RUBBERIZED CONCRETE AT HIGH VOLUME FRACTIONS AND RUBBER-BINDER COMPOSITES

8.1. INTRODUCTION

This part of the investigation focuses on the use of waste rubber particles in non structural engineering composites. The concept is to use large portions of waste rubber in civil engineering applications. This section consists mainly of two parts. The first part investigates the use of crumb rubber particles as a replacement of fine aggregate. Crumb rubber was used as a replacement by volume of sand by 20%, 40%, 60%, 80% and 100%. The second part contains the use of different types of rubber particles with cement or epoxy as a binder. Also, surface treatment of rubber particles was used in rubber composites to enhance the surface texture of rubber particles.

8.2. RUBBERIZED CONCRETE AT HIGH VOLUME FRACTIONS OF SAND REPLACEMENT

8.2.1. Thermal Conductivity Test

Thermal properties are very important in many construction applications. When a temperature gradient exists, there is an energy transfer from the high temperature region to the low temperature region. It can be said that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient. Thermal conductivity (k) has been determined for both conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles using Lee method for bad conductors.

The thermal conductivity of conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles is shown in Figure 5.1 and Table 5.1. From this table, the thermal conductivity of conventional concrete is 1.45 W/m.Cº, while the k-values of rubberized concrete at rubber volume fractions 20%, 40%, 60%, 80% and 100% are 0.96, 0.85, 0.73, 0.67 and 0.6 W/m.Cº, respectively. From the test results, it can be concluded that, thermal conductivity of concrete decreases with the increase in rubber content. Furthermore, the reduction in k-values at 20% and 100% rubber content is 34% and 59%, respectively, comparing to that for conventional concrete.

Rana H [31] also evaluated thermal conductivity for rubberized concrete using the same technique used in this study. Rana reported the same reduction in thermal conductivity for rubberized concrete, as the reduction in k-value is 26.7% at 15% rubber content comparing to that for traditional concrete.

Also, P. Sukontasukkul [30] studied the thermal properties at different percentages of sand replacement by rubber particles using the hot plate method. Sukontasukkul concluded that, the reduction in thermal conductivity of rubberized concrete at 10% and 30% fine aggregate replacement by weight is about 20% and 50%, respectively. The k-values achieved by Sukontasukkul are lower than the k-values presented in the present study. This may be attributed to the smaller rubber particles and different test method that was used by Sukontasukkul.

Thermal resistance "R" (m^2/K. W) of 50mm thickness panels are calculated based on Eq. 5.1 [57, 58, 73], as t is the panel thickness (m) and k is the thermal conductivity (W/m.Cº)

$$\boldsymbol{R = \frac{t}{k}} \text{ ....} \textbf{Eq. 5.1}$$

Table 5.2 presents the thermal resistance (R) of conventional concrete and rubberized concrete at different rubber contents. From this table, it can be seen that rubberized concrete, even at low rubber contents, yields higher thermal resistance than conventional concrete.

The correlation between the thermal conductivity (W/m. Cº) and density (kg/m^3) is shown in Figure 5.2. This correlation can be expressed by the equation;

$$\mathbf{K = 0.018e^{0.00181d}} \text{ .... } \textbf{Eq. 5.2}$$

Where d is density (kg/m^3) and K is the thermal conductivity (W/m. Cº)

The relation between thermal conductivity and concrete density for conventional concrete is expressed by ACI 122R as follows;

$$\mathbf{K = 0.072\ e^{0.00125d}} \text{ ....} \textbf{Eq. 5.3}$$

The ACI model is also plotted in Figure 5.2. From this figure, it can be seen that, the equation provided by ACI 122R is not applicable with rubberized concrete. As the actual K-values are lower than the valued derived from Eq 5.3.

Table 5.1 Thermal conductivity (K) for conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles

Sand replacement by rubber %	Thermal conductivity K (W/m. Cº)	Reduction (%)
Control	1.45	-
20%	0.96	-34%
40%	0.85	-41%
60%	0.73	-50%
80%	0.67	-54%
100%	0.60	-59%

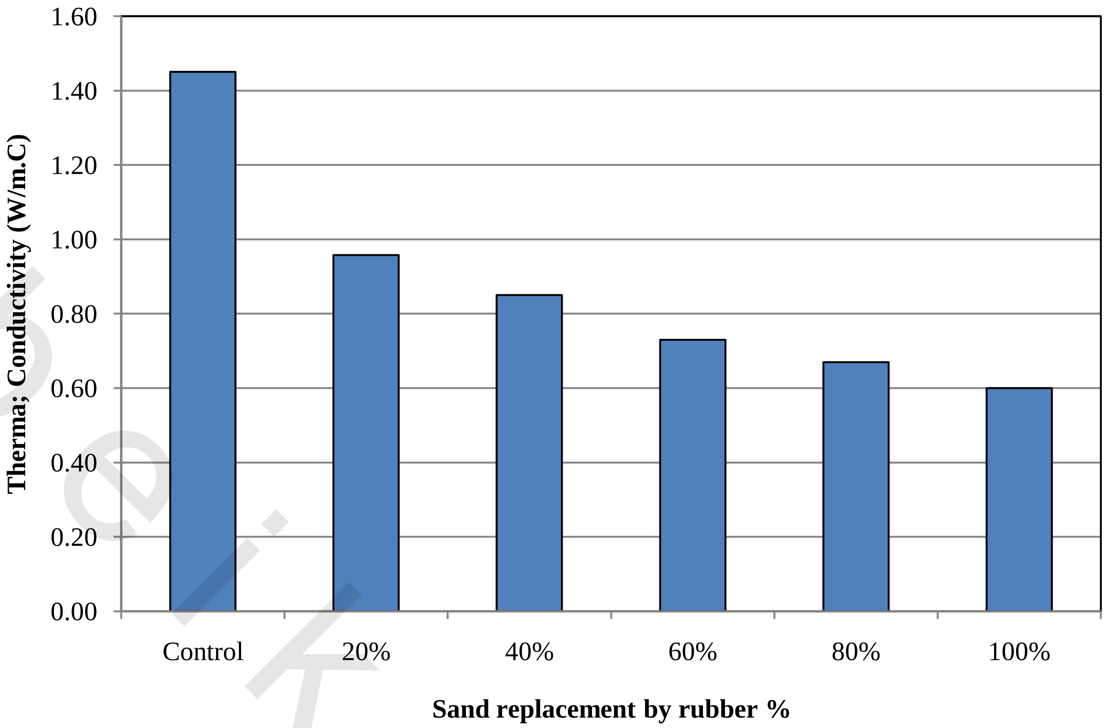

Figure 5.1 Thermal conductivity (K) for conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles

Table 5.2 Thermal resistance (R) for 50mm thickness panels of conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles

Sand replacement by rubber %	Thermal resistance R (m^2/K. W)	Reduction (%)
Control	0.034	-
20%	0.052	-51%
40%	0.059	-71%
60%	0.068	-99%
80%	0.075	-116%
100%	0.083	-142%

8.2.2. Sound Attenuation Test

The sound attenuation coefficient (α) herein is determined by measuring the reduction in amplitude of an acoustic wave. Sound waves propagate through material by the combined effect of scattering and absorption as $\alpha = \alpha_{scattering} + \alpha_{absorption}$. The value of $\alpha_{scattering}$ is related to grain size in polycrystalline materials and $\alpha_{absorption}$ is related to phenomena such as; energy loss by internal friction (viscosity), thermal conductivity, relaxation, variation in molecules kinetic energy, variations in density, diffusion due to pressure gradient and thermo diffusion [59, 60]. Attenuation is generally proportional to the amplitude change of decaying sound wave. There are a lot of techniques that are used to determine the sound attenuation coefficient. In the present study, the amplitude of the electric input signal was held constant throughout the experimental series, so changes in the amplitude can be attributed directly to the attenuating behavior of the material.

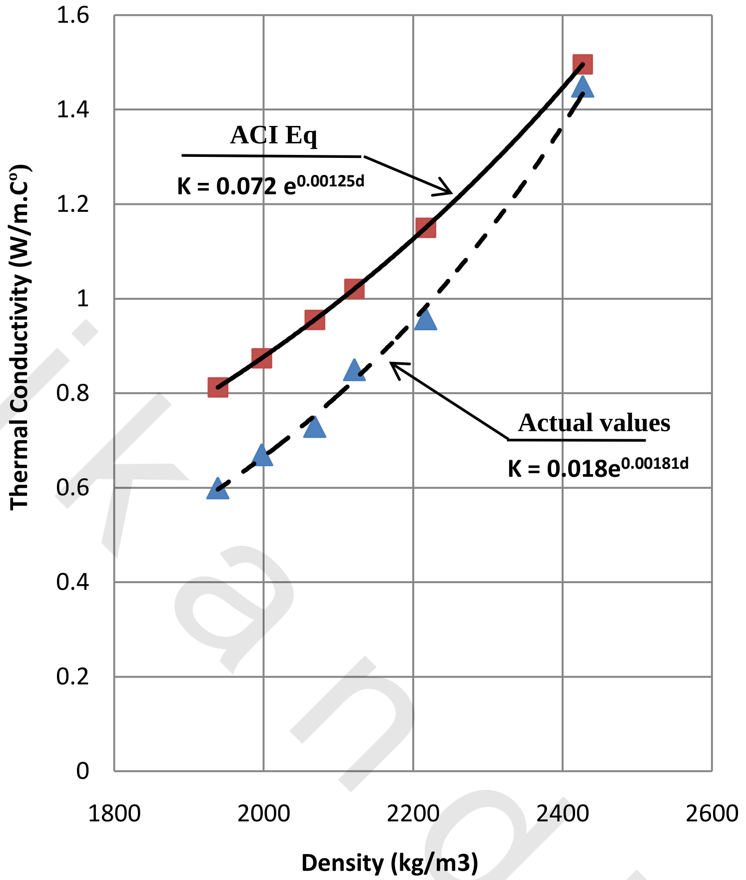

Figure 5.2 The correlation between the thermal conductivity and density

Attenuation coefficient of conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles is shown in Table 5.3 and Figure 5.3. It can be seen that, the attenuation coefficient increases with the increase in rubber content. This increase in sound attenuation coefficient indicates a better sound insulation of rubberized concrete. Also, Table 5.3 indicates that the increase of sound attenuation comparing to conventional concrete is 14%, 24%, 46%, 58% and 69% at percentages of sand replacement by rubber particles 20%, 40%, 60%, 80% and 100%, respectively.

The test results of Sukontasukkul [30] confirm the same sound insulation properties of rubberized concrete. Sukontasukkul stated that rubberized concrete achieved higher noise reduction coefficient comparing to that of conventional concrete. This finding is also confirmed by the results in this study as sound absorption is a part of sound attenuation, based on the fact that $\alpha = \alpha_{scattering} + \alpha_{absorbtion}$. C. Albano [33] stated that the enhancement of sound attenuation is attributed to the porosity of rubberized concrete which influences directly the propagation of sound waves.

In addition, these results agree with Saleem's [32] work but less improvement in sound insulation was found .Saleem found that, sound insulation for rubberized concrete increases by only 19% at 100% replacement of coarse aggregate.

Table 5.3 Attenuation coefficient of normal concrete and rubberized concrete at different rubber contents

Sand replacement by rubber %	Attenuation coefficient (dB/mm)	Increase (%)
Control	0.75	-
20%	0.85	14%
40%	0.92	24%
60%	1.09	46%
80%	1.18	58%
100%	1.26	69%

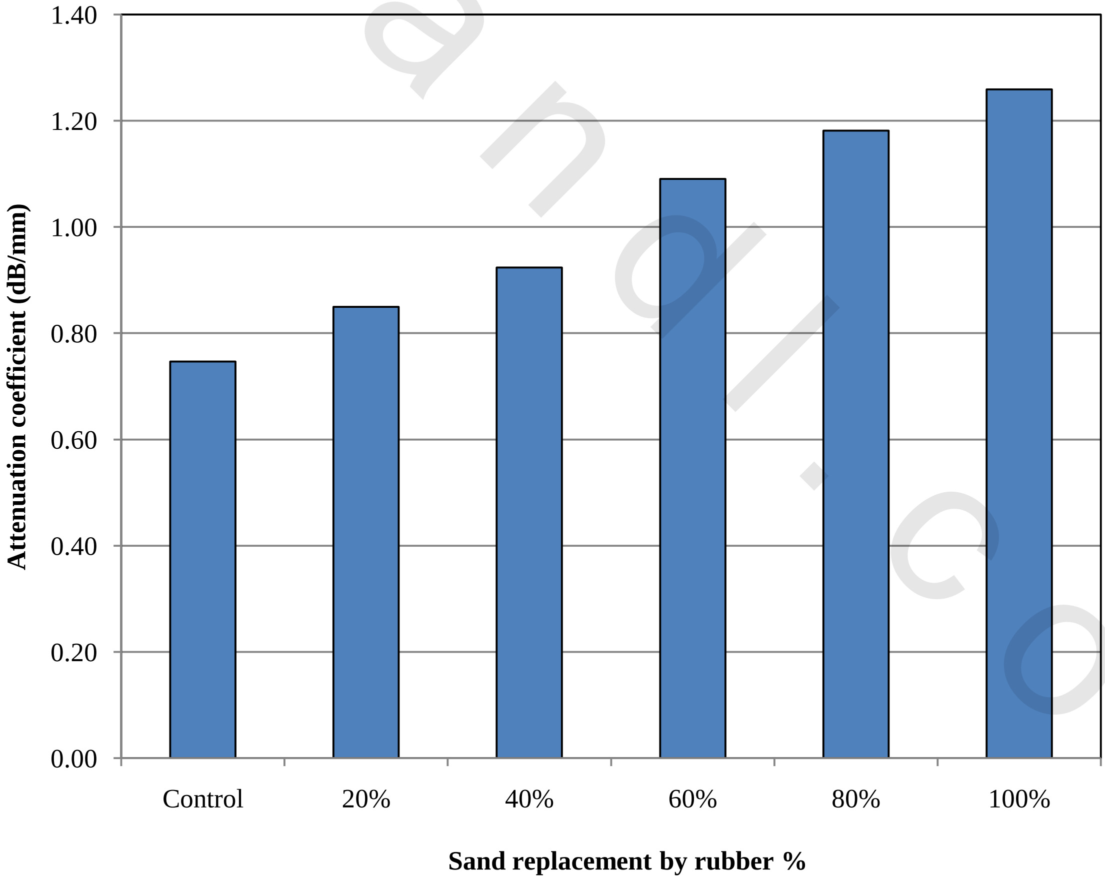

Figure 5.3 Attenuation coefficient of normal concrete and rubberized concrete at different percentages of sand replacement by rubber

8.2.3. Hardened Properties of Rubberized Concrete

Although, the purpose of this work is to utilize waste rubber in concrete for non structural applications, physical characteristics and mechanical properties of rubberized concrete were determined. In general, it was found that the mechanical properties of concrete strongly affected negatively by the increase in rubber content.

8.2.3.1. Density and water absorption

Table 5.4, Figures 5.4 and Figure 5.5 present the density and water absorption of conventional and rubberized concrete at different percentages of sand replacement by rubber. From which, it can be seen that the density decreases gradually with the increase in rubber content. This behavior may be attributed to the less density of rubber material. The maximum reduction in density was recorded by 20% at 100% replacement of fine aggregates. Also, the water absorption increases with the increase in percentages of sand replacement by rubber.

The same results were reported in the investigation by Rostami et al. [44] and Topcu [3]. Rosstami and Topcu indicated that concrete densities were reduced by 13% and 33%, respectively, when maximum amounts of rubber were used as replacement of fine or coarse aggregate or both.

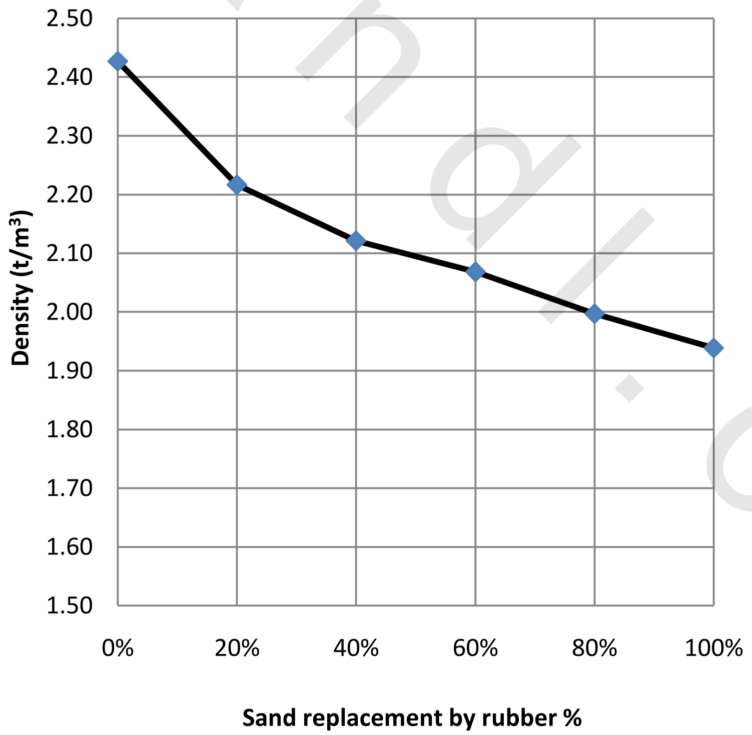

Figure 5.4 Density at different percentages of sand replacement by rubber

Table 5.4 Density and water absorption of conventional and rubberized concrete at different percentages of sand replacement by rubber.

Sand replacement by rubber %	Density (t/m3)	Reduction in density (%)	Water absorption (%)
Control	2.43	0	3.62
20%	2.22	9	4.88
40%	2.12	13	5.20
60%	2.07	15	6.30
80%	2.00	18	6.89
100%	1.94	20	7.00

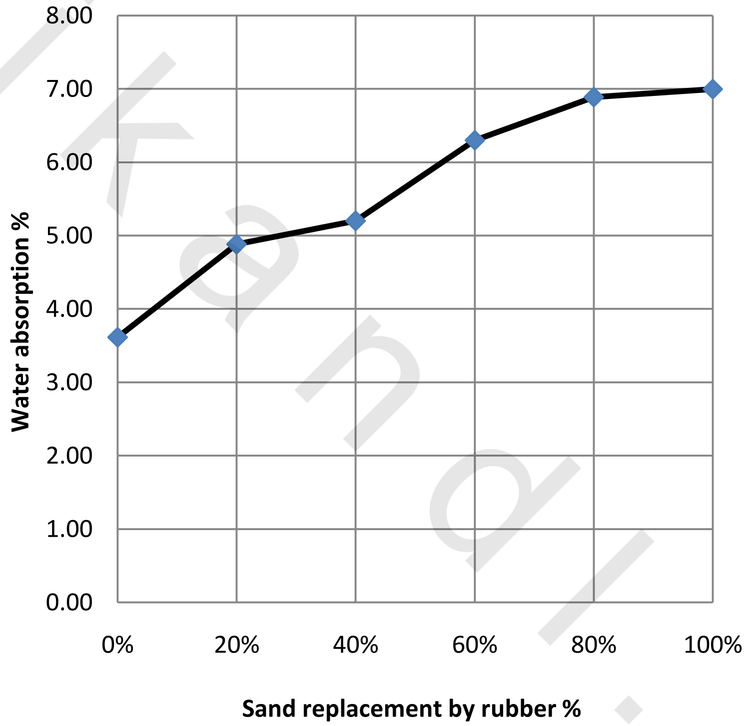

Figure 5.5 Water absorption at different percentages of sand replacement by rubber

8.2.3.2. Compressive strength test

The cube compressive strength test results for conventional and rubberized concrete at different percentages of sand replacement by rubber are illustrated in Table 5.5 and Figure 5.6. The results show that the cube compressive strength decreases significantly with the increase in the percentage of sand replacement by rubber. From Table 5.5, it is noticed that the maximum reduction in compressive strength for rubberized concrete is 93.3% at 100% fine aggregate replacement. Furthermore, it was observed during the compression test, that rubberized concrete samples with percentages of sand replacement by rubber particles 60%, 80% and 100% do not exhibit brittle failure under compression due to the rubber's plastic behavior. Previous investigators also reported the same ductile behavior for rubberized concrete at high volume fractions [3, 11, 17, 23 and 24].

The same reduction in compressive strength is reported by Elgammal [22], Topcu [3] and Elsenouci [18]. The observed reduction in rubberized concrete compressive strength with the increase in rubber content may be attributed to two reasons, as illustrated by Bayomy [17], Topcu [3] and Elsenouci [18]. First, the rubber particles are much softer than the surrounding matrix, so cracks are initiated quickly around the rubber particles in the mix, which accelerates the failure of concrete. The second reason is the lack of adhesion between the rubber particle and the paste, as soft rubber particles may behave like voids in concrete.

Table 5.5 Cube compressive strength at different percentages of sand replacement by rubber particles after 7, 14 and 28 days

Cube compressive strength (Mpa)				
Sand replacement by rubber %	**After 7 days**	**After 14 days**	**After 28 days**	**Reduction after 28 days (%)**
control	29.89	33.18	39.32	0.00
20%	18.82	21.67	23.04	41
40%	10.15	11.66	12.62	68
60%	8.95	10.155	11.465	71
80%	3.22	3.96	4.205	89
100%	2.05	2.57	2.63	93

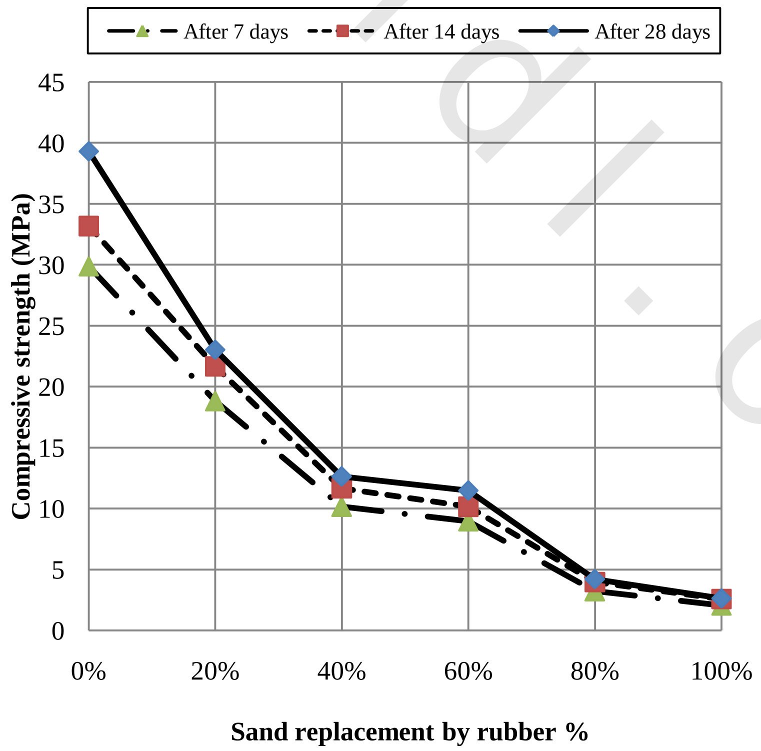

Figure 5.6 Cube compressive strength at different percentages of sand replacement by rubber

8.2.3.3. Impact resistance test

Table 5.6 and Figure 5.7 summarize the drop weight test results for conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles. The impact resistance is evaluated by the number of blows corresponding to the first visual crack and number of blows corresponding to fracture. From the test results, it can be seen that the first crack and failure impact resistance of rubberized concrete decrease significantly with the increase in rubber content. The number of blows corresponding to first crack decreases by 29%, 69%, 78%, 86% and 71% for rubberized concrete at percentages of sand replacement by rubber particles 20%, 40%, 60%, 80% and 100%, respectively, compared with conventional concrete. This may be attributed to the poor adhesion between rubber particles and cement paste [8].

Table 5.6 Drop weight test results at different percentages of sand replacement by rubber

Sand replacement by rubber %	No. of blows		Reduction (%)		No of blows for crack propagation
	Initial crack	failure	Initial crack	failure	
Control	130	139	0	0	9
20%	92	109	29	22	17
40%	40	60	69	57	20
60%	28	50	78	64	22
80%	18	42	86	70	24
100%	38	63	71	55	25

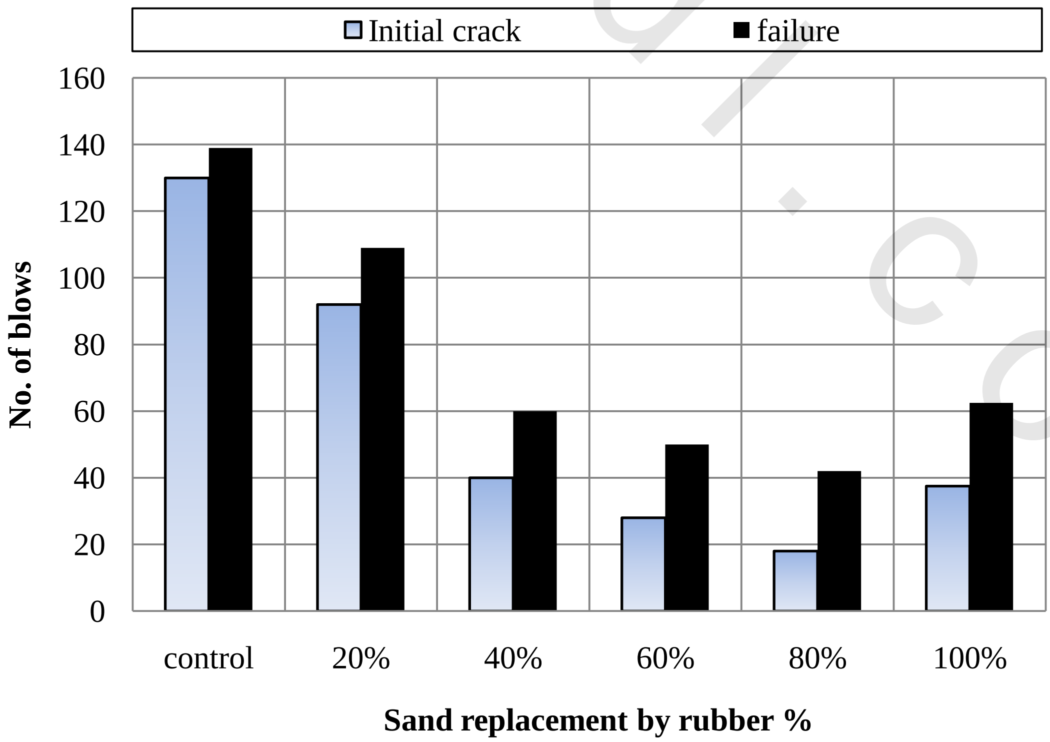

Figure 5.7 Drop weight test results at different rubber contents

Also, the number of blows corresponding to crack propagation is calculated, as shown in Figure 5.8. This is the difference between the number of blows causing the first visual crack and that causing fracture. From this figure, it is noticed that the number of blows corresponding to crack propagation improves with the increase in the percentage of sand replacement by rubber particles. This may be attributed to the fact that rubber particles enhance the ability of concrete to absorb energy, as stated by Siddique[8]. It is also noticed that rubberized concrete at high volume fractions insulate sound during impact. The same results are reported by Topcu [3] and Senouci [18].

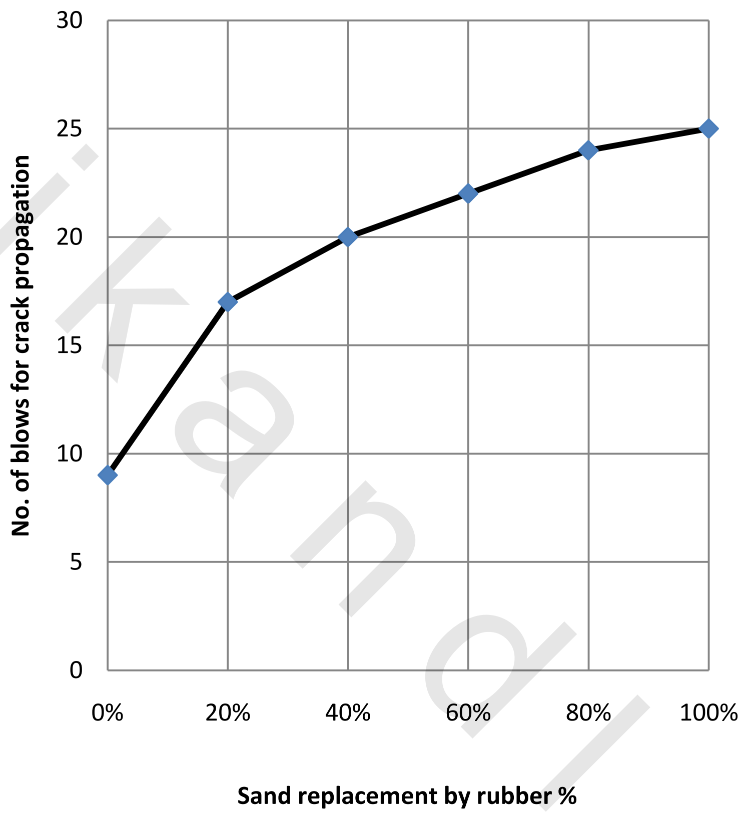

Figure 5.8 Number of blows for crack propagation

8.2.3.4. Flexural strength test

The flexural strength test results of conventional concrete and rubberized concrete are illustrated in Table 5.7, Figure 5.9 and Figure 5.10. From the test results, the flexural strength of conventional concrete decreased significantly with the inclusion of rubber particles. The reductions in flexural strength are 32%, 60%, 62%, 80% and 84% at percentages of sand replacement by rubber particles 20%, 40%, 60%, 80% and 100%, respectively. Moreover, despite of the significant decrease in flexural strength for rubberized concrete, the maximum mid span deflection increased with the increase in the percentage of sand replacement by rubber particles, as can be noticed from Table 5.7.

Table 5.7 Flexural strength and maximum deflection at different percentages of sand replacement by rubber particles

Sand replacement by rubber %	Flexure strength (MPa)	Reduction (%)	Maximum deflection (mm)
Control	4.84	0%	0.52
20%	3.28	32%	0.45
40%	1.92	60%	0.55
60%	1.83	62%	0.91
80%	0.96	80%	2.00
100%	0.76	84%	2.50

Microscopic observations by Hai Huynh [23] showed that, fracture occurs at the rubber-cement interface and pull-out failure is observed. Khatib and Bayomy [17] reported a similar behavior for rubberized concrete, as the specimen exhibit elastic deformations and the specimens tend to fail gradually. Also, Tocpu [3] reported that, with the increase in rubber content, concrete becomes comparatively ductile and begins to show an elastic behavior. Topcu also stated that, in spite of the decrease in rubberized concrete flexural strength, some changes are witnessed in the energy capacities consumed during the fracture. Topcu attributed this behavior to the fact that rubberized concrete absorb more energy due to the inclusion of rubber particles.

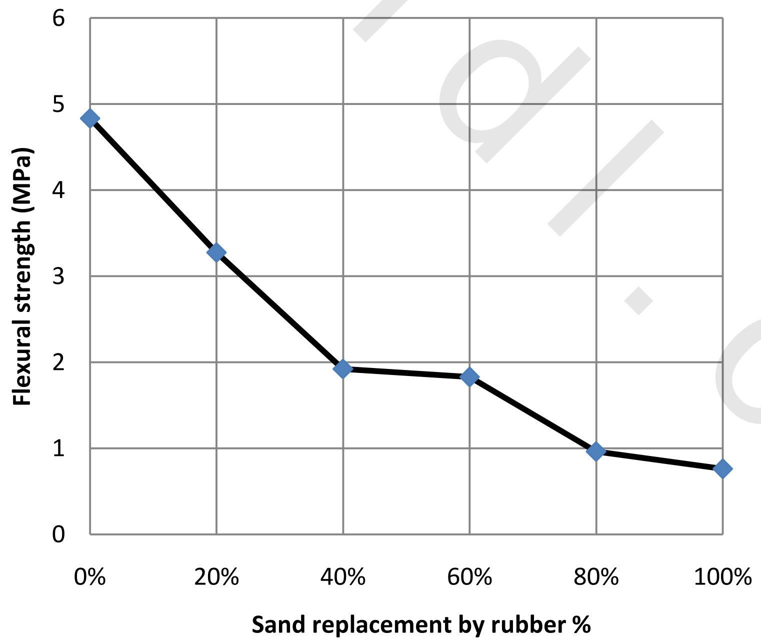

Figure 5.9 Flexural strength at different percentages of sand replacement by rubber

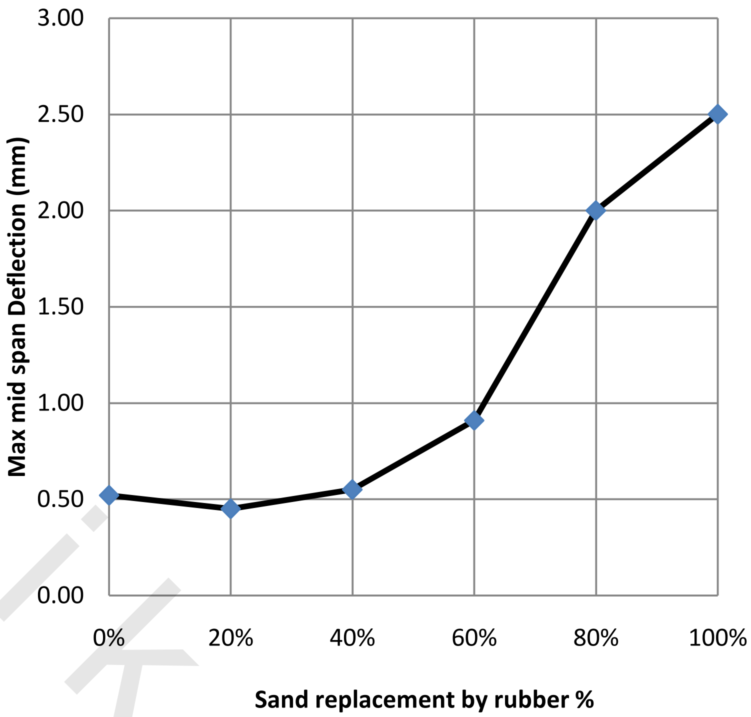

Figure 5.10 Flexural maximum deflections at different percentages of sand replacement by rubber

5.3. RUBBER-CEMENT AND RUBBER-EPOXY COMPOSITES

This part includes the test results for rubber-cement and rubber-epoxy composites. Sound and thermal insulation properties were evaluated to determine the ability of the rubber composites to be used as insulation panels comparing to the currently used materials. Also, the rubber composites were subjected to repeated loading cycles until failure.

5.3.1. Thermal Conductivity Test

Rubber-cement and rubber-epoxy samples for thermal conductivity test are presented in Figure 5.11. Thermal conductivity of rubber-cement and rubber-epoxy composites was evaluated using Lee method for bad conductors. Table 5.8 and Figure 5.12 summarize the thermal conductivity test results for rubber-cement and rubber-epoxy composites. From the test results, it can be seen that, rubber geometry has a significant effect on thermal conductivity. Crumb rubber gives the best thermal insulation properties for both cement and epoxy composites. The results showed that, the least K-value is given by crumb rubber-epoxy composites (0.2 W/m.C^o), while the highest K-value is given by Fiber 4-cement composite (0.55 W/m.C^o). Also, it can be conducted that, the thermal conductivity of rubber-epoxy composites is much lower than the thermal conductivity of rubber-cement composites. The average thermal conductivity of rubber-epoxy composites is lower than the average of rubber-cement composites by about 46%.

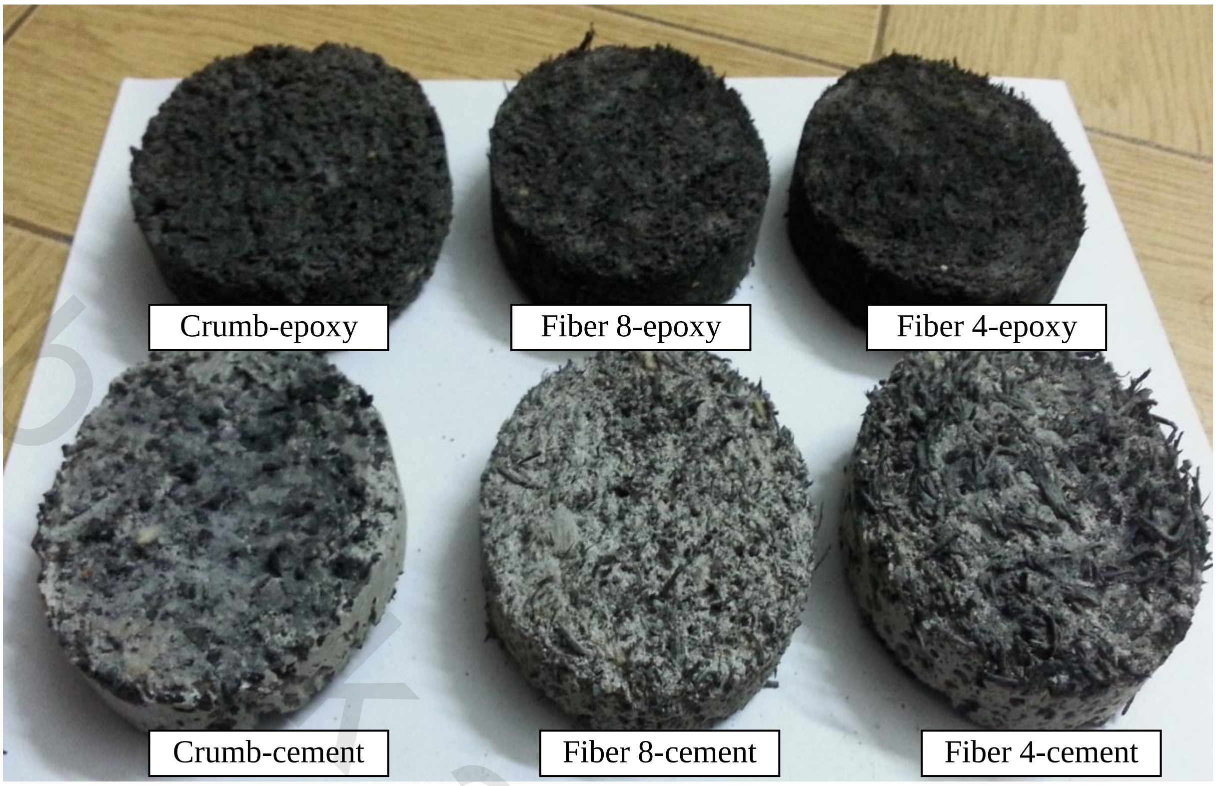

Figure 5.12 Rubber-cement and rubber-epoxy samples for thermal conductivity test

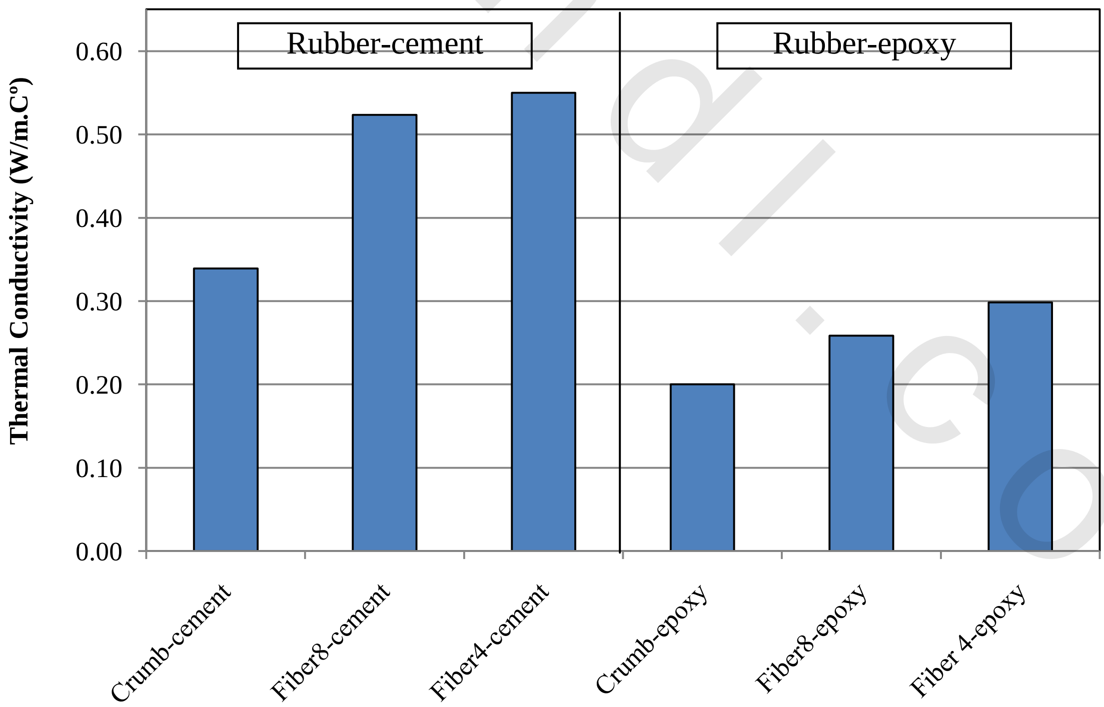

Figure 5.11 Thermal conductivity (K) for rubber-cement and rubber-epoxy composites

Table 5.8 Thermal conductivity (K) for rubber-cement and rubber-epoxy composites

Rubber content	Thermal conductivity K (W/m. Cº)
Crumb-cement	0.34
Fiber8-cement	0.52
Fiber4-cement	0.55
Crumb-epoxy	0.20
Fiber8-epoxy	0.26
Fiber 4-epoxy	0.30

Table 5.9 illustrates the thermal conductivity of some common materials and the averages of k-values of rubber composites presented in this study. The gypsum board is the most common material used as false ceiling and partition walls. In fact, the thermal conductivity of gypsum is about 0.17 to 0.23 W/m.Cº, which is quite similar to rubber-epoxy composites. In addition, one of the main advantages of commercial gypsum boards is the ease of cutting and formation. Also, it was noticed that, rubber-epoxy composites can be nailed with no difficulties and no cracks appear after nailing vice versa the common gypsum ceiling boards.

Furthermore, From Table 5.9, rubber composites has lower thermal conductivity than other lighter materials. As the thermal conductivity of Foamed concrete and autoclave concrete is 0.7 and 0.6W/m.Cº, According to ACI 122R-02.

Table 5.9 Thermal conductivity of some common materials

Material	Thermal conductivity K (W/m. Cº)
Clay brick	0.82
Foamed concrete	0.7
Autoclaved concrete	0.6
Rubber-cement composites	0.47
Rubber-epoxy composites	0.25
Gypsum boards	0.17-0.23
Extruded polystyrene boards	0.03

5.3.2. Sound Attenuation Test

The sound attenuation coefficient was determined for both rubber-cement and rubber-epoxy composites with different rubber types, as shown in Table 5.10 and Figure 5.12. From the test results, it can be seen that, the attenuation coefficient varied with the change in rubber type and binder. In general, rubber-cement composites give slightly better results than rubber-epoxy composites. In fact, crumb rubber-cement composite seems to be the best sound insulator material for each composite.

To evaluate the improvement in sound insulation properties of the rubber composites, the results were compared to rubberized concrete from section 5.2.2. It can be seen that, sound attenuation of crumb rubber-cement composite is 34% higher than rubberized concrete with 100% rubber content. This can be attributed to the fact that rubber composites consists mainly of rubber particles without mineral aggregate. S.Herrero [34] stated that rubber has good properties to dissipate dynamic energy which improve the sound insulation performance of the composite.

Table 5.10 Attenuation coefficient of rubber-cement and rubber-epoxy composites

Rubber content	Attenuation coefficient (dB/mm)
Crumb-cement	1.69
Fiber8-cement	1.64
Fiber4-cement	1.28
Crumb-Epoxy	1.60
Fiber8-Epoxy	1.45
Fiber4-epoxy	0.98

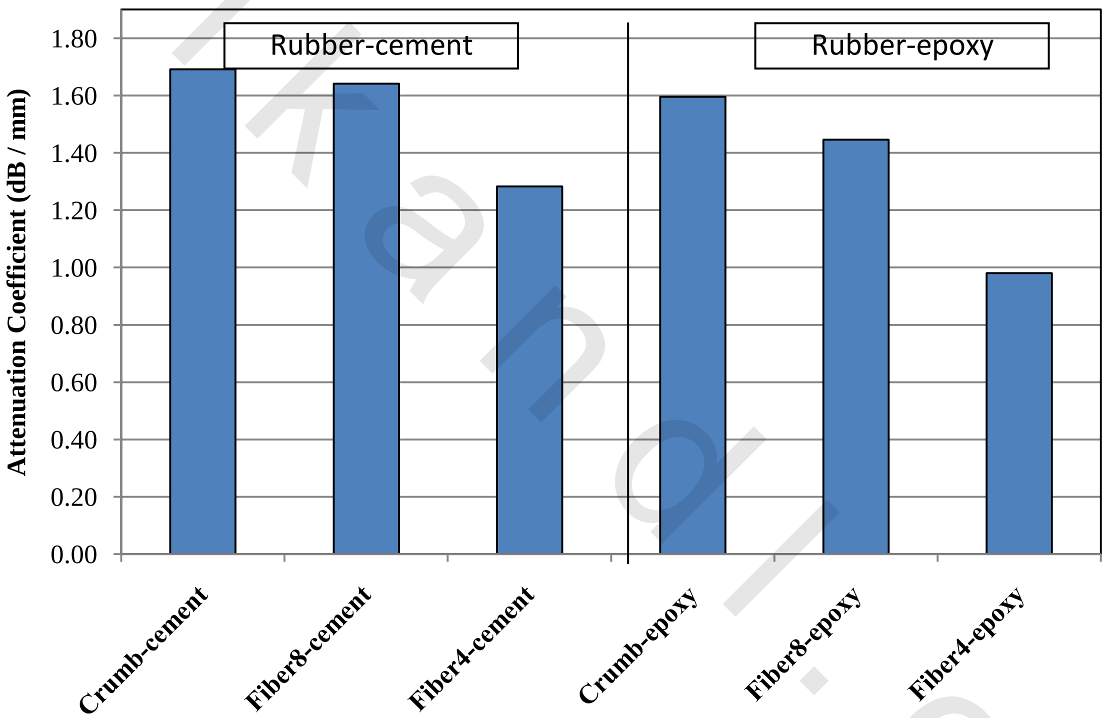

Figure 5.12 Attenuation coefficients of rubber-cement and rubber-epoxy composites

5.3.3. Hardened properties of rubber-binder composite

In this section, the dry unit weight was determined for rubber-cement and rubber-epoxy composites. Furthermore, the compressive strength of the composites was determined and the behavior of rubber composites under repeated load was also described in this section.

The dry unit weight of rubber-cement and rubber-epoxy composites is shown in Figure 5.13. From the test results, it can be noticed that, rubber-epoxy composites are lighter than rubber-cement composites by 30% in average. Also, rubber type has insignificant affect on dry unit weight. In addition, based on the unit weight test results only, rubber composites may be considered as a light weight material.

Cylinder specimens of rubber composites were subjected to compression load and the displacements were recorded to construct the stress-strain relationship of the composites. Figure 5.14 shows the used specimens of rubber-cement and rubber-epoxy composites. The compressive strength test results for the composites were evaluated according to ASTM D1621, as shown in Table 5.9. From this table, it is obvious that rubber-cement composites have low compressive strength comparing to rubber-epoxy composites. In addition, it is also observed that, the best compressive strength values for both cement and epoxy composites are achieved by Fiber 4. Moreover, the shape of failure under compression load for rubber-cement and rubber-epoxy composites are sown in Figure 5.15 and Figure 5.16.

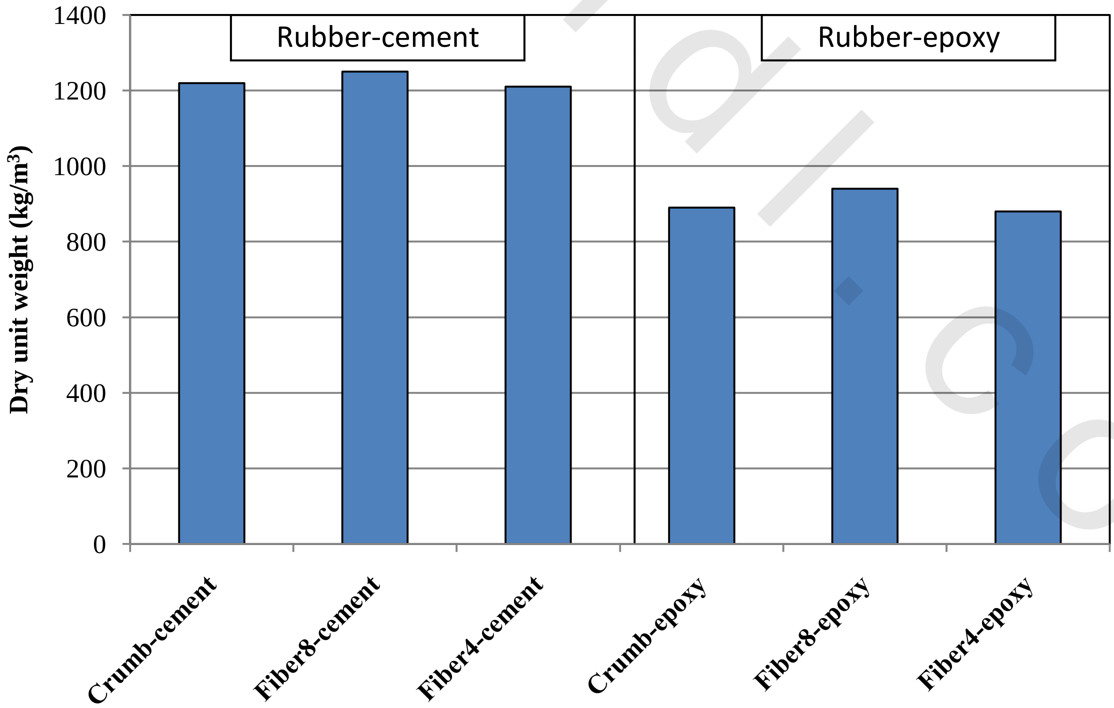

Figure 5.13 Dry unit weight of rubber-cement and rubber-epoxy composites

Figure 5.14 The specimens of rubber-cement and rubber-epoxy composites.

Rubber composite	Compressive strength (MPa)
Crumb-cement	0.36
Fiber8-cement	0.34
Fiber4-cement	0.57
Crumb-Epoxy (at 75% deformations) According to ASTM D1621	3.62
Fiber8-Epoxy (at 75% deformations) According to ASTM D1621	5.66
Fiber4-epoxy (at 75% deformations) According to ASTM D1621	6.11

Also Figure 5.17 and Figure 5.18 summarize the stress-strain curve for rubber-cement composites and rubber-epoxy composite. It can be seen that rubber-epoxy composites exhibit a significant ductile behavior, especially for Fiber 8 and Fiber 4, compared with rubber-cement composites. Also, it is noticed that, the Fiber 8 and Fiber 4 rubber-epoxy composites exhibit an elastic behavior where these composites almost retain to its original dimensions after unloading, as shown in Figure 5.19

As a result of the elastic behavior of rubber-epoxy composites, it was decided to subject these composites to repeated cycles of loading till failure. The rubber-epoxy composite of Fiber 8 has the ability to withstand three loading cycles without significant loss in the strength, as shown in Figure 5.20. For rubber-epoxy composite with Fiber 4, the composite withstands 8 cycles of loading and unloading, as seen in Figure 5.21.

However, Figure 5.20 and Figure 2.21 show the compressive strength at 75% deformation at each cycle of loading. From these figures, it can be noticed that the strength at 75% deformation decreases with the increase in number of loading cycles till failure. Also, the shape of Fiber 4–epoxy composite after the first load cycle and after 8 cycles is revealed in Figure 5.22.

a) Crumb rubber

b) Fiber 8

c) Fiber 4

Figure 5.15 The shape of failure under compression load for rubber-cement composites

a) Crumb rubber

b) Fiber 8

c) Fiber 4

Figure 5.16 The shape of failure under compression load for rubber-epoxy composites

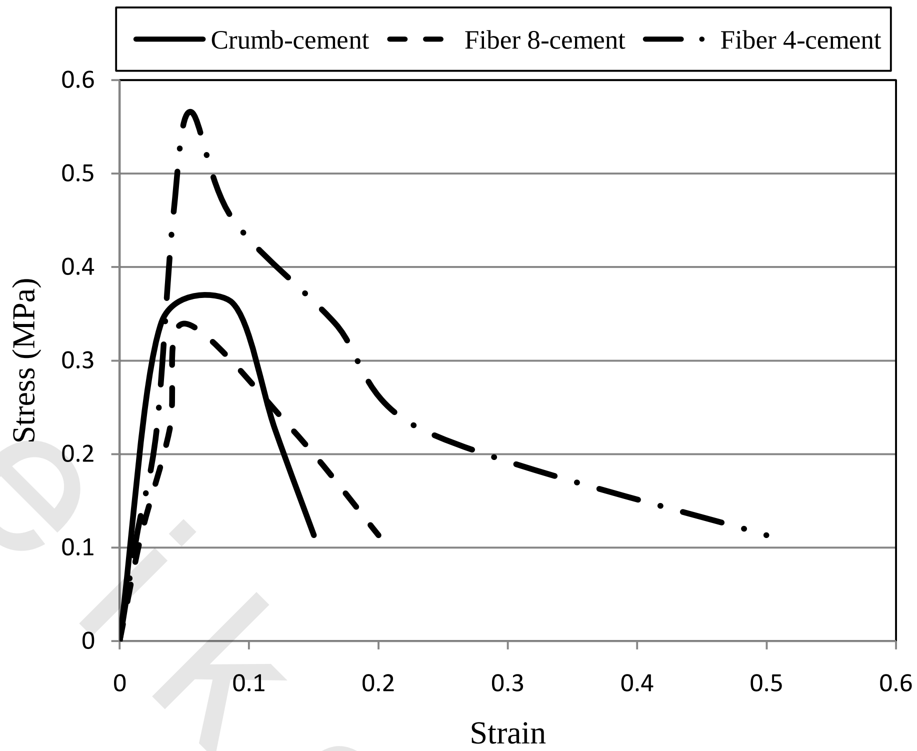

Figure 5.17 The stress-strain curve for rubber-cement composites

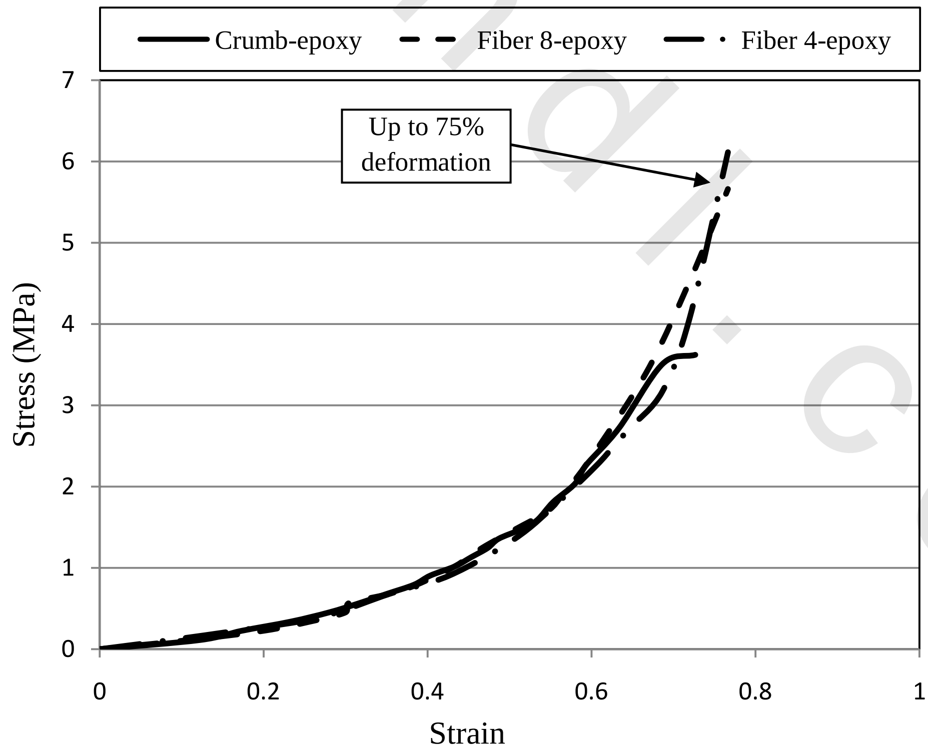

Figure 5.18 The stress-strain curve for rubber-epoxy composites

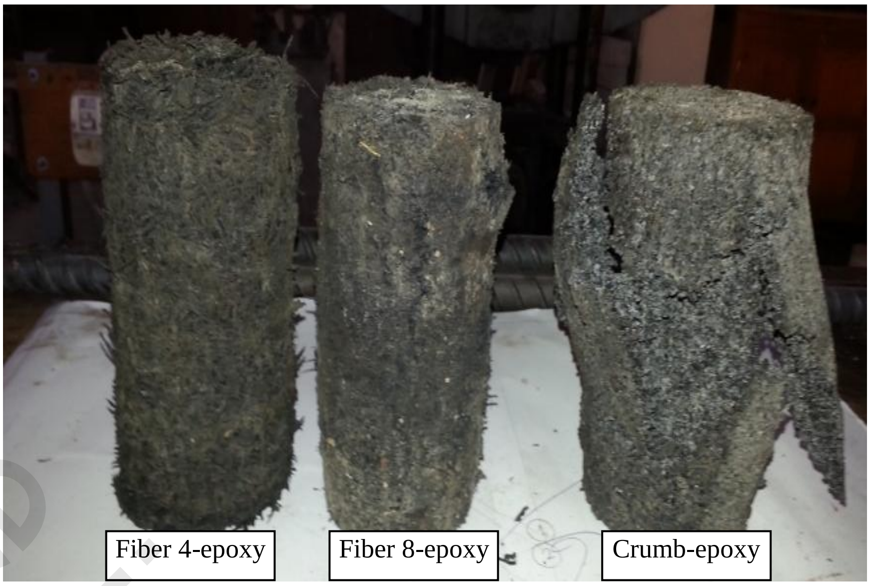

Figure 5.19 Rubber-epoxy specimens after the first cycle of loading

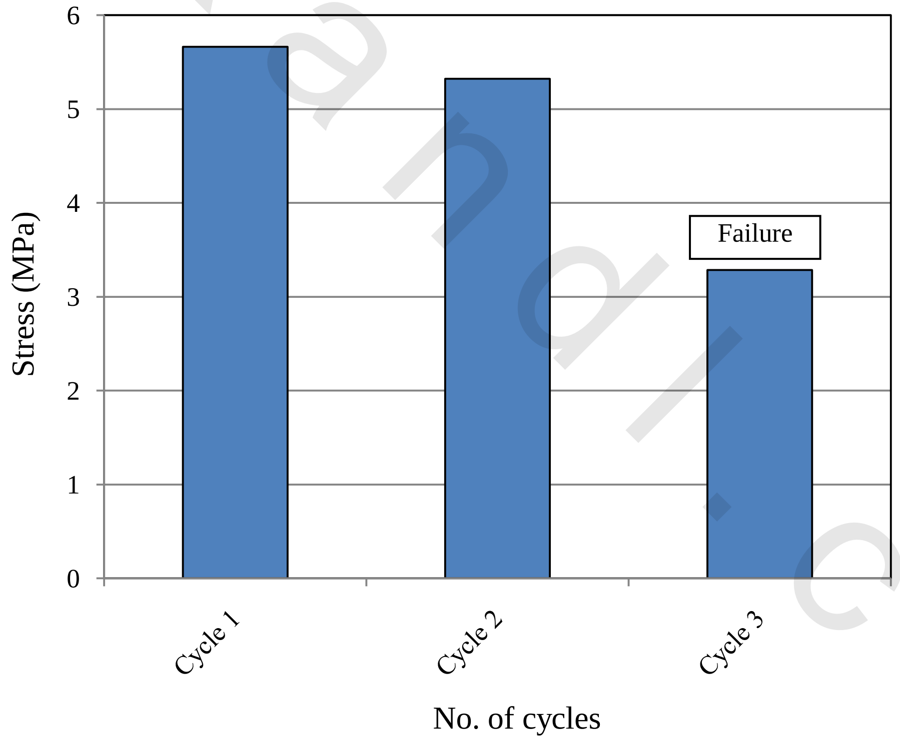

Figure 5.20 The loading cycles of rubber-epoxy composite with Fiber 8

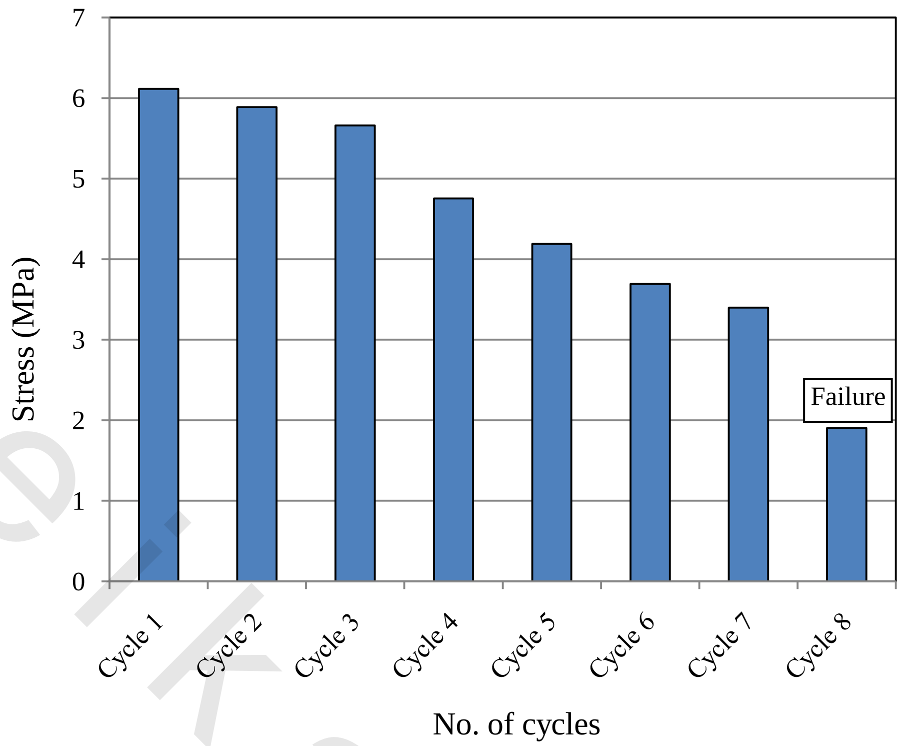

Figure 5.21 The loading cycles of rubber-epoxy composite with Fiber 4

(a) (b)

Figure 5.22 Rubber epoxy composite with Fiber 8 after one loading cycle (a) and eight cycles of loading (b)