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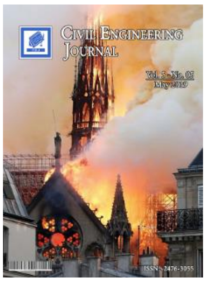

A Comparative Study on the Flexural Behaviour of Rubberized and Hybrid Rubberized Reinforced Concrete Beams

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Abstract

This paper aims to investigate the flexural behaviour of the rubberized and hybrid rubberized reinforced concrete beams. A total of fourteen beams, 150×200 mm in cross-section with 1000 mm in length, were subject to a laboratory test over an effective span of 900 mm. The sand river aggregate was replaced by 10%, 12.5%, and 15% of crumb rubber (volume). The hybrid structure contained two double layers: 1) rubberized reinforcement concrete at the top layer of the beam and 2) reinforcement concrete at the bottom layer of the concrete beam. The static responses by the flexural test of all the beams were evaluated in terms of their fresh properties, failure patterns, total energy, flexural strength, stiffness, and ultimate deflection, modulus of rupture, strain capacity, and ductility index. The results showed that there were improvements when the hybrid beams were used in most cases such as failure pattern, ultimate load, stiffness, modulus of rupture, and stress. The rubberized concrete beams showed improvements in the strain capacity as illustrated in strain gauges and stress-strain curves, toughness, ultimate deflection, and ductility index. The findings of the study revealed an improved performance with the use of the hybrid beams. This has resulted in the implementation of innovative civil engineering applications in the engineering sustainable structures.

Keywords: Rubberized Concrete; Hybrid-Rubberized Concrete; Crumb Rubber; Double Layers.

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1. Introduction

There exist billions of scrap car tires per annum, which represents a significant environmental issue around the globe [1]. Significant benefits can, therefore, be achieved when these expired tires are reused in different civil engineering applications such as concrete. Sustainable concrete can be obtained and the dangerous substances of tires in the environment can be reduced [2]. Regarding such a critical environmental issue, studies (small-scale specimens) were published during the last twenty years. These studies focused on the use of crumb rubber particles as an alternative to using sand aggregates replacement at different ratios. The findings showed a decrease in the mechanical properties of concrete and low workability, which were increased when the percentage of rubber replacement increased [3]. However, different findings revealed that toughness, strain capacity, ductility, and cracking resistance and reduction of self-weight have improved [4, 5]. Ismail et al. [6] Conducted flexural testing in large-scale of structural beams made of rubberized concrete ranged from 5 to15% of fine aggregate replacement. They pointed out that, with the increase of crumb rubber it will lead to the reduction of crack widths and increased the number, reduce self-weight of concrete, decrease in toughness when exceeded 15% of crumb rubber contents. Another study on large scale beams was carried out by Mendis et al. [7] to evaluate the efficacy of different ratio of crumbed rubber on beams with and without shear reinforcements.

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It was found that the rubber contents influenced the shear capacity, yet, the relationship between the rubber ratio and shear capacity were not sufficient for the determination. Therefore, the confidence level of using crumb rubber still needs to be build up to be effectively used in structural members with a new arrangement and design of material distribution in the concrete mix.

This means that the hybrid concrete structures can be used to remove some obstacles because of using the crumb rubber in conventional concrete. This can be useful for improving the confidence level. Mohankar et al. [8] defined the term ‘hybrid’ as a composite of two or several types of materials with different shapes or dimensions. Commercial products that combine various types of materials (such as steel and plastic) in concrete composites are widely available [9].The hybrid structure in the construction industry is a combination of two layers containing the precast and in-situ concrete. This type of structure has special conditions and it undergoes a specific process for construction based on the client’s requirements [10]. In the context of this study, the hybrid concrete structure is significant because it is a combination of two or more different materials within the concrete, which can improve the hardened properties [11].

Promising results have been reported in previous studies that investigated the hybrid structure on a small scale including the rubberized concrete. Li et al. [12] investigated the isolated hybrid structure, which consists of two layers: the rubberized concrete was placed at the bottom of the beams up to 30% of their overall depth and the rest was filled with normal concrete. The findings revealed that these types of structure were useful in reducing the structure response when exposed to load. In another study, Al-Tayeb et al. [13] investigated the rubberized concrete and the hybrid structure by using a prism adding 5%, 10%, and 20% of rubber. The hybrid structure consists of two layers: the rubberized concrete layer and the normal concrete layer. The rubberized concrete was placed on the top of the layer and was filled up to the height of 50 %. The normal concrete was put at the bottom of the beams. The findings revealed better performance in dynamic loading than in static loading.

Norman [14] investigated small-size beams of rubberized and hybrid-rubberized concrete under static and dynamic load. The main variables in the experiment were crumb rubber with different percentages (5%, 10%, 15%, 17.5 %, 20%, 22.5%, and 25%) of partial replacement of fine aggregate located at the top of 50 % in height for the hybrid structure. The plain concrete was placed at the bottom. The results showed that the hybrid structure with a rubberized layer at the top absorbed high flexural energy in an impact load than in a static load. Previous studies tested the hybrid members that include the rubberized concrete. For example, Abqari [15] carried out a comparative study including the rubberized concrete and hybrid-rubberized concrete beam with two layers. The top was given for conventional concrete, while the bottom was given for rubberized concrete at 20% of the volume for fine aggregate replacement. Their height of filled are based upon the neutral axis. The results revealed that the performance was the same for the rubberized reinforced concrete beam and the hybrid reinforced concrete beam during the first crack loading. However, the results revealed that the stiffness of the hybrid structure exhibited better performance than the rubberized concrete. This can be attributed to the hybrid reinforced concrete beam deflection, which is slightly lower than the rubberized reinforced concrete beam.

Upon reviewing the previously conducted studies in this section, it can be concluded that there is a gap in the literature. This gap is related to the flexural behaviour of the rubberized and hybrid rubberized reinforced concrete beams at a large scale. Therefore, the main purpose of this study is to examine the flexural behaviour of a novel type of hybrid reinforced concrete beams with the top layer that consists of rubberized concrete at 10%, 12.5%, and 15% by volume of fine aggregate. This paper contributes to sustainable concrete structures by providing a potential concrete structure application, which is used in various practical works.

2. Experimental Program

2.1. Materials

One of the materials that were used in the experimental works is type 1 of ordinary Portland cement with a relative density of 3.15. The natural crushed aggregate of 10 mm maximum size and natural river sand were used as coarse aggregates and fine aggregates, respectively. The relative density, fineness modulus and absorption of fine aggregates were 2.64%, 3.40%, and 1%, respectively. A crumb rubber aggregates with a maximum size up to 4.75 mm, with a specific gravity of 1.22. The gradation curves for coarse, fine and rubber aggregate was obtained by sieve analysis as illustrated in Figure1.Superplasticizer (SP) was used with a specific gravity of 1.06 to adjust the workability of the mixture.

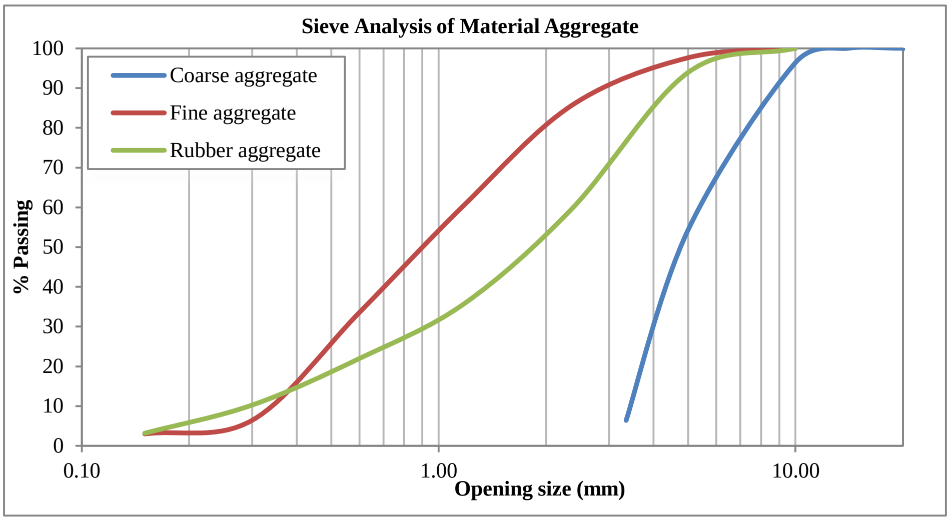


Figure 1. Grading curves of aggregate materials

2.2. Concrete Mixtures

Seven mixtures were prepared, and each mix consisted of three cylinders of 100 mm in diameter and 200 mm in height, three cubes of 100 mm size, two beams of 1000 ×150×200 mm dimensions that were reinforced with four bars of 10 mm longitudinal reinforcement and stirrups of 6 mm in diameter for shear at 125 mm spacing between center to center as shown in Figure 2. All the steel bars had an average yield stress of 428 MPa. The controlled specimens were prepared without any inclusion of crumb rubber, while three mixtures of rubberized concrete were prepared with the inclusion of crumb rubber ratio at 10%, 12.5%, and 15% of fine aggregate replacement. The hybrid structure was cast into two equal layers. The first layer was for normal concrete, whereas the second layer was for rubberized concrete and it consists of three mixture types based on the percentage of crumb rubber which varied from 10% to 15%. The details of the rubberized and hybrid rubberized concrete beams, cubes, cylinder, and its mix proportions are illustrated in Figure 3 and Table1.

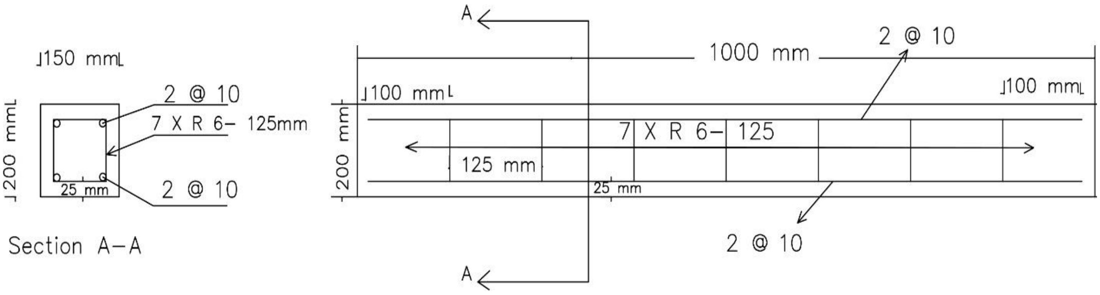
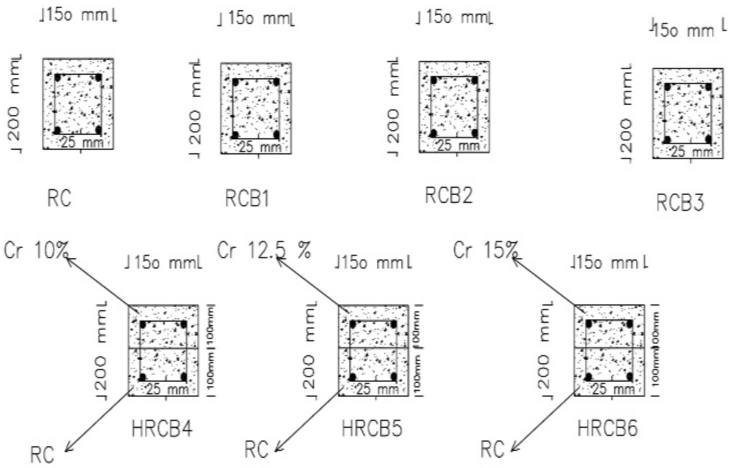
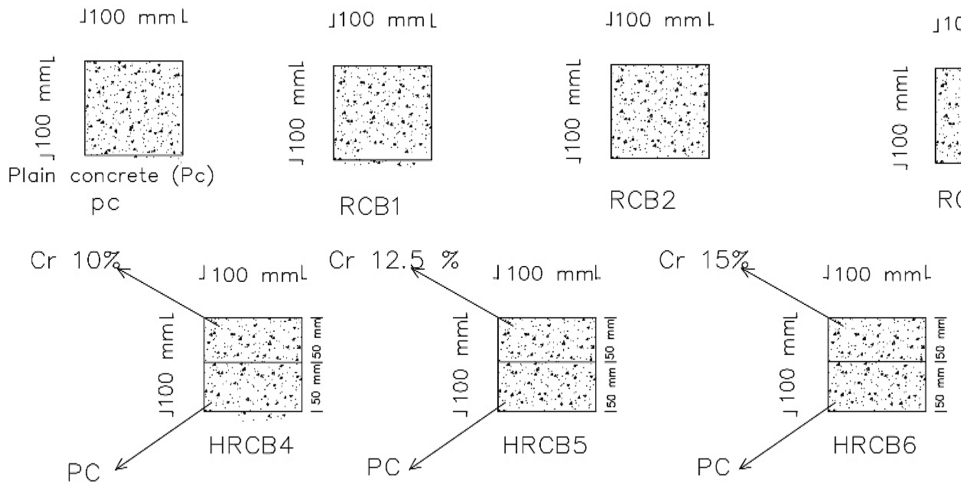


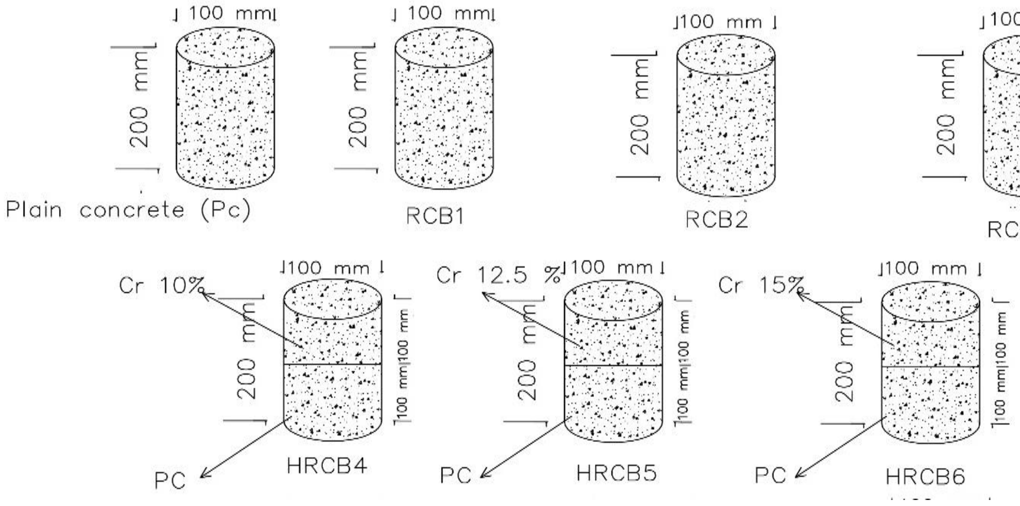
Figure 2. Beam Configuration



Beams sections



Cubes sections



Cylinders sections

Figure 3. Details of Rubberized and Hybrid Rubberized Concrete

Table 1. Concrete mix designs a) Controlled and rubberized concrete, b) Hybrid-rubberized concrete

(a)

Type of Mix		Cement (kg/ m³)	Coarse Aggregates (kg/ m³)	Water (kg/ m³)	Fine Aggregates (kg/ m³)	Crumb rubber (kg/ m³)		Superplasticizer (kg/ m³)
Type	Name					% Cr	(kg/ m³)	
Controlled	RC	360	1060	173	713	0	0	0.9
Rubberized concrete	RCB1	360	1060	173	641.7	10 %	32.86	1.08
	RCB2	360	1060	173	623.88	12.50%	41.08	1.08
	RCB3	360	1060	173	606.05	15%	49.38	1.08

(b)

Type of Mix		Cement (kg/ m³)	Coarse Aggregates (kg/ m³)	Water (kg/ m³)	Fine Aggregates (kg/ m³)		Crumb rubber (kg/ m³)		Superplasticizer (kg/ m³)	
Type	Name				First layer	Second layer	% Cr	(kg/ m³)	First layer	Second layer
Hybrid Rubberized concrete	HRCB4	360	1060	173	641.7	713	10.00%	32.86	1.08	0.9
	HRCB5	360	1060	173	623.88	713	12.50%	41.08	1.08	0.9
	HRCB6	360	1060	173	606.05	713	15.00%	49.38	1.08	0.9

3. Testing

3.1. Mechanical Properties Testing

A total of 63 specimens by 21 and 42 for cube and cylinders, respectively were cast according to ASTM C192 [16] for each mixture. In the hybrid (layered), cube and cylinder were cast with the same mixture at the time of casting the reinforcement beams for each layered as shown in Figure 4. The compressive strength, split test, density, and modulus elasticity were determined after curing was complete for 28 days in conditions that were like those of the tested beams. Figure 5 shows the research methodology of this study for materials properties and reinforcement beams.

Figure 4. Cast and Test of Hybrid Structure for Standard Specimens

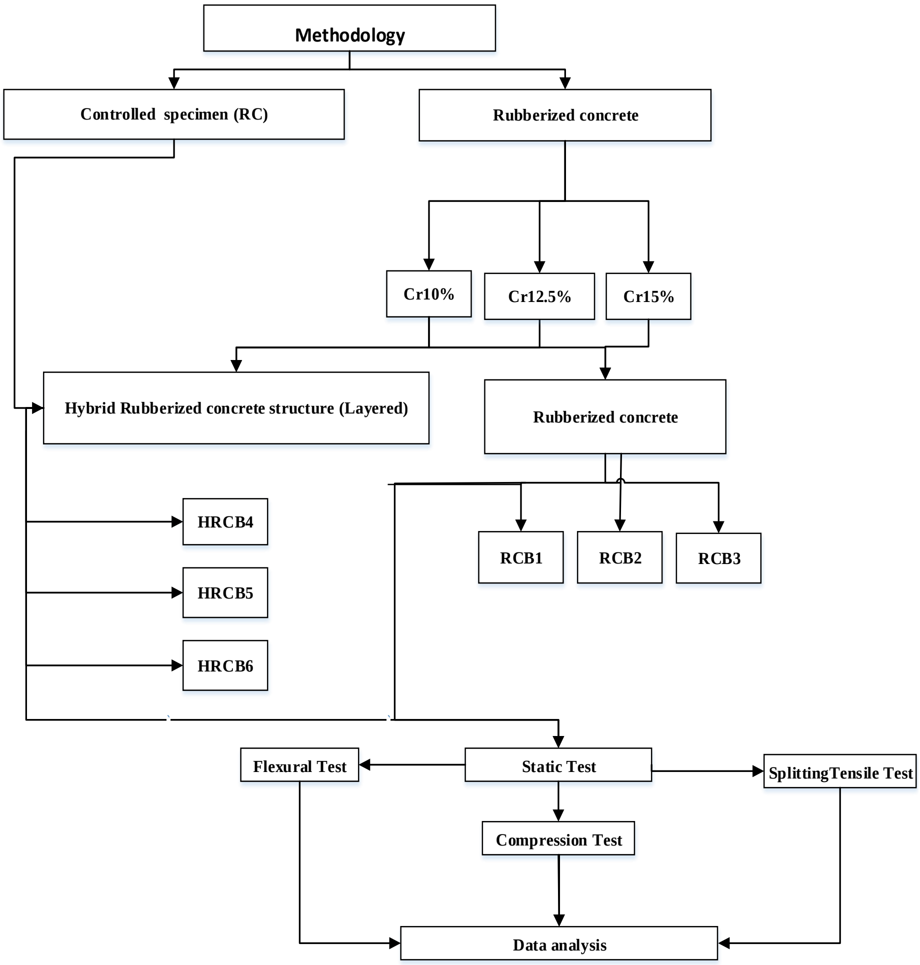


Figure 5. Research methodology flowchart

3.2. Flexure Test Setup, Instrumentation, and Loading Procedure

The beams were tested under four points load to determine its flexural strength. The linear variable differential transformer (LVDT) was used to record and measure the mid-span deflection until failure. A strain gauge was mounted at the main bottom steel bar and at the top middle of the concrete surface with different lengths to measure the strain during the loading. This strain gauge was manufactured by electronic instrument-Japan. In this strain gauge, 30 mm length used for concrete, while 5 mm length for longitudinal reinforcement. An incremental load was applied to the tested beams, while the first crack was monitored and observed by the naked eye at different levels of loadings (first cracking load and ultimate load). These were detected, marked, photted, and recorded. The details of the testing setup are shown in Figure 6.

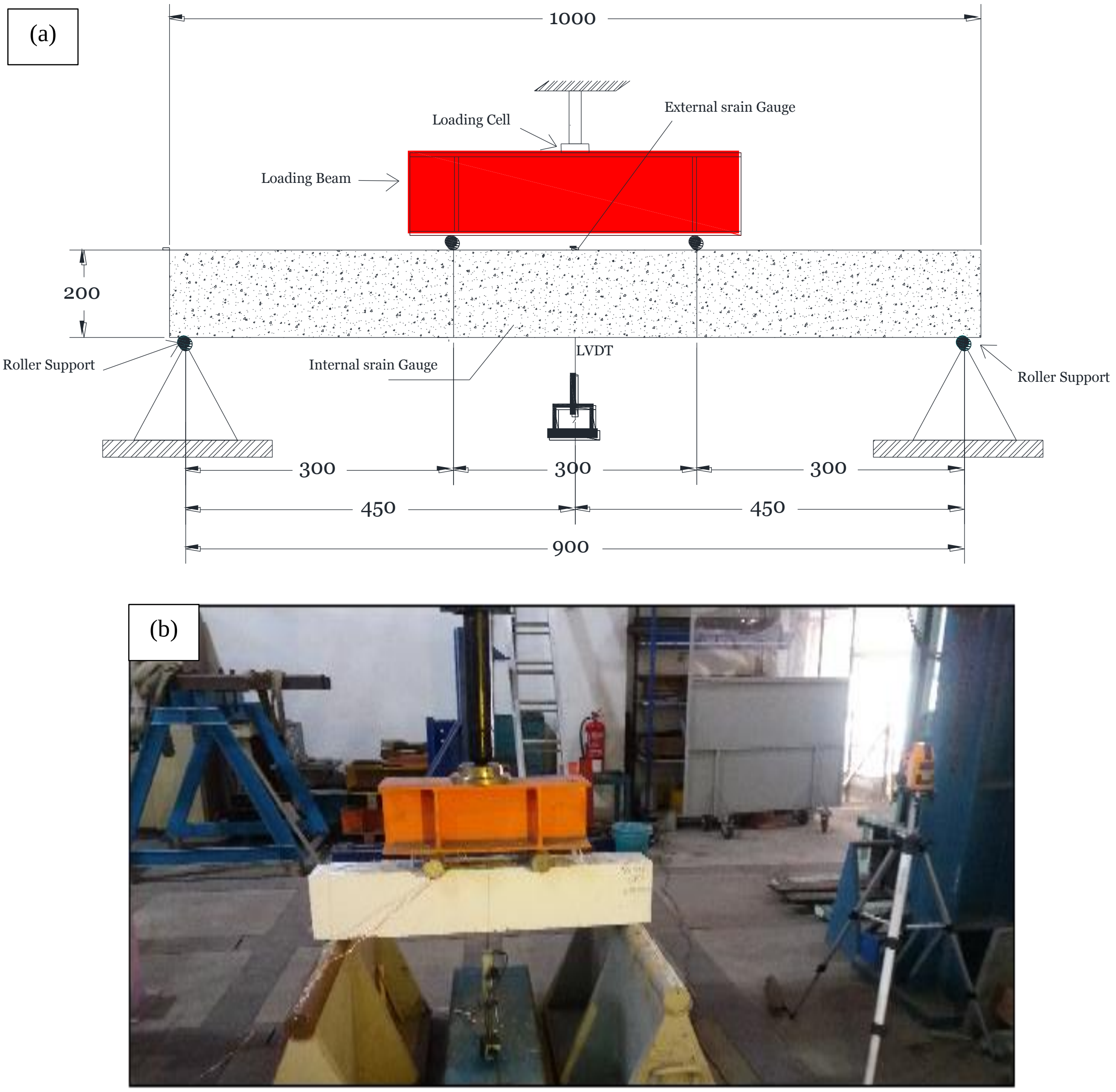


Figure 6. Beam Set-up a) Schematic Beams Test, b) Real Beams Test

4. Results and Discussion

4.1. Mechanical Properties

Table 2 illustrates the three specimens' average of the mechanical properties (compressive strength, split tensile strength, and static modulus of elasticity) of all the mixtures under a similar condition like the structural arrangement to that of the tested beams. In general, the reductions accrued in the overall results of the mechanical properties at the age of 28 days with increasing the crumb rubber ratios from 10% to 15%. By examining mixture RC (the controlled one) to RCB3 (15Cr), the compressive strength for cubes dropped from 8.2 % to 16.5% at crumb rubber percentage, which varies from 10% to 15% by replacement of sand, respectively. Several studies have previously reported the decline in compressive strength subjected to rubber contents by revealing the negative effect [6, 14, 17, 18]. The nature of the crumb hydrophobic allowed to increase the voids by air in the concrete mixtures and lead to concentrate the stress across micro cracks that caused by rubber thereby reduction in hardness strength [19]. The reductions of compressive strength at the same ratios of crumb rubber contents were considerably higher in-cylinder, which ranged from 24.1% to 40%. The huge reductions can be mainly attributed to the cylindrical shape and ratio of the height to diameter as indicated by Yi et al. [20].

Table 2. Results of the mechanical properties

Types of mix	Compressive strength, fc' (MPa)		Density (kg/m³)	Static modulus of elasticity (GPa)	Split tensile strength, fsp (MPa)
	Cubes	Cylinder			
RC (Controlled)	48.5	41.30	2370.12	31.9	3.6
RCB1	44.5	31.35	2292.62	26.4	3.2
RCB2	42.9	26.68	2269.01	24.0	2.8
RCB3	40.5	24.75	2259.12	23.0	2.7
HRCB4	46.4	34.11	2323.93	28.1	3.4
HRCB5	44.5	28.56	2309.33	25.5	3.3
HRCB6	42.9	26.41	2289.71	24.2	2.9

The hybrid cubical and cylindrical structure contains rubberized concrete at the top and normal concrete at the bottom. There was a lower decrement (improvement) in compression strength compared to non-hybrid (RC, RCB1, RCB2, and RCB3). It was varied in cubes from 2.9 to11.6. However, in the cylindrical structure, it ranged from 17.4% to 36.1% at 10 to 15 % of crumb rubber volume, respectively. This is because the rubber contents to half of the volume specimens compared fully specimen's rubberized concrete. Similar effects of crumb rubber were obtained in density as illustrated in Table 2 for the rubberized and hybrid rubberized concrete in each mixture. These results were compared with previous studies [6, 18, 21-22] that were conducted on the rubberized concrete only. One possible justification is that the relative density of sand in this study was doubled at 2.65 in contrast with the relative density of crumb rubber at 1.22. Zheng et al. [23] supported this reason and argued that the lower specific gravity of crumb rubber can be attributed to this reduction with various outcomes based on the practical size of rubber. Also, Richardson et al [24] reported that 1.5% of fine aggregate replacement by crumb rubber weight lead to increasing in the air content by 26%, consequently decreasing the density by 2%.In contrast, the hybrid cubical and cylindrical structure showed an increase in the overall unit density than the rubberized concrete. The modulus of elasticity can be calculated directly based on the ACI formula [25] as shown below:

$$E = Wc^{1.5} X\ 0.043\sqrt{fc} \tag{1}$$

Where E = The modulus of elasticity (GPa), Wc = cube density (kg/ m³), fc = Compressive strength of cylinder (MPa).

Ahmed [14] and Zheng [23] used this expression to predict the modulus of elasticity based on the cube's density (Kg/m³) and compressive cylinder strength (MPa) values, which were obtained based on their experiment. According to Table 2, there are strong relationships between the compressive strength and the modulus of elasticity in reductions that are subject to crumb rubber contents. It is also expected that these reductions exist because the fine aggregate had a higher modulus of elasticity in contrast with the crumb rubber aggregate [14]. In the hybrid structure, the reduction of a modulus of elasticity has improved from 4% to 5% approximately compared with the fully rubberized concrete at 10%, to 15% of crumb rubber ratios.

The splitting tensile results were followed by the reductions of compressive strength and the modulus of elasticity that were caused by incorporation of the crumb rubber as a partial replacement of fine aggregates. The value results of controlled splitting strength were 3.60 MPa. After that, it decremented to 3.16, 2.83, and 2.73 MPa when the fine aggregate was partially replaced by the crumb rubber at 10, 12.5, and 15%. This finding was found to be inconsistent with previous studies' findings [6, 14, 20, 21]. In the cylindrical hybrid structure, there was an improvement in splitting tensile by 8.2 %, 16%, and 5%, respectively when compared with the rubberized concrete at 10 %, 12.5%, and 15%. Half of the volume specimens was filled with the rubberized concrete and the other was filled with the normal concrete. Such results can be considered as potential reasons for those experimental results.

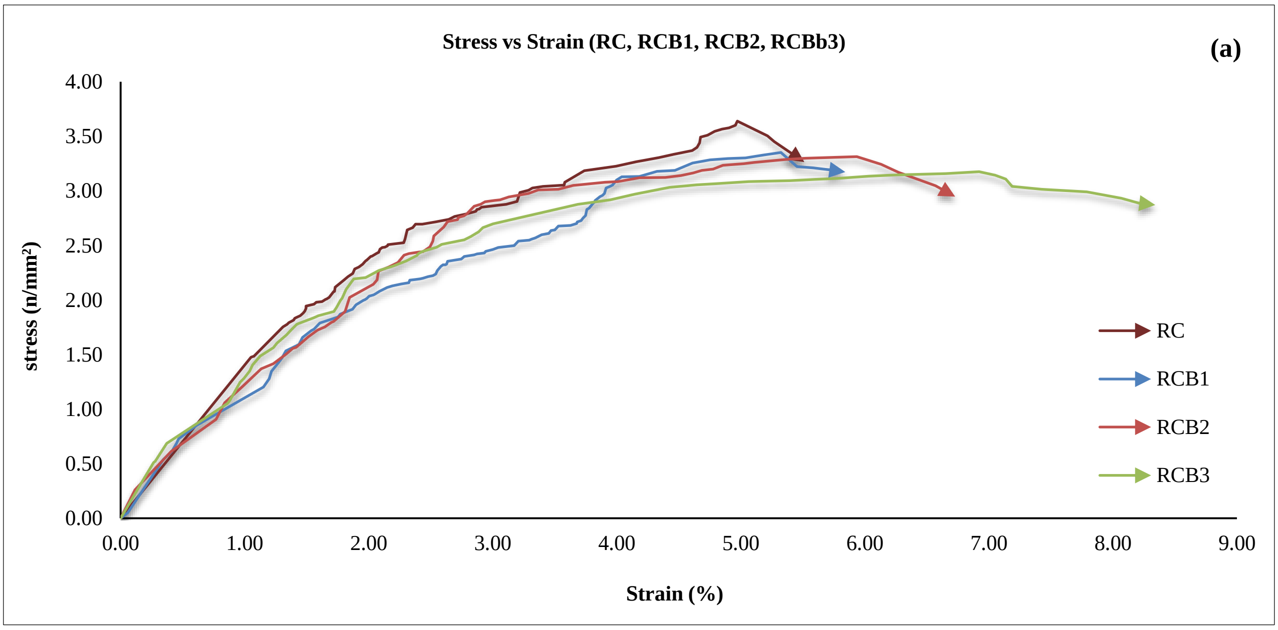
4.2. Ultimate Flexural Strength and Strains Capacity

Table 3 presents the ultimate flexural strength, which was obtained from the load-deflection curve of the tested beams and, accordingly, the effectiveness of crumb rubber on Modulus of rupture by a reduction increased the rubber ratio. It was decreased in an average from 16.38 to 14.29 MPa to 13% approximately compared with the controlled specimens. Ahmed et al. [21] reported that the increase in rubber content in concrete mixtures caused a reduction in flexural strength. Table 3 illustrates that the rates of the decreased flexural strength in the hybrid beams structure were better in contrast with the rubberized concrete without the layer due to the reduction in the rubber contents. Norman [14] reported that the rubberized layer at the top of the hybrid concrete was directly subject to load and absorbed more energy, whereas the bottom of the plain concrete demonstrated more tensile resistance.

Table 3. Results of the ultimate flexural strength and strain capacity

Type of Mix	Flexural strength (Mpa)	Average (Mpa)	stress σcr (N/mm²)	Average (N/mm²)	Stress συ (N/mm²)	Average (N/mm²)	From load-strain curve				From Strain gauges recorded at ultimate load ευ (mm/mm)×10⁻⁶			
							Strain εcr (%)	Average	Strain ευ (%)	Average	longitudinal reinforcement at tension zone εcυ	Average	concrete strain εcυ	Average
RC	17.56	16.39	1.55	1.53	3.90	3.64	1.25	1.08	5.52	4.97	409.00	397.50	-1268.00	1217.50
	15.21		1.50		3.38		0.90		4.42		386.00		-1167.00	
RCB1	16.63	15.09	1.39	1.39	3.70	3.36	1.22	1.21	5.88	5.33	433.00	481.00	-1328.00	1355.50
	13.54		1.39		3.01		1.20		4.77		529.00		-1383.00	
RCB2	13.52	14.92	1.29	1.30	3.01	3.32	1.27	1.23	5.34	5.94	597.00	589.00	-1364.00	1405.50
	16.32		1.31		3.63		1.19		6.53		581.00		-1447.00	
RCB3	15.37	14.29	1.28	1.29	2.94	3.18	1.23	1.24	6.22	6.92	698.00	648.50	-1522.00	1614.50
	13.21		1.30		3.42		1.24		7.62		599.00		-1707.00	
HRCB4	15.96	16.04	1.40	1.40	3.55	3.57	1.14	1.10	4.18	4.31	305.00	343.50	-1190.00	1337.50
	16.11		1.40		3.58		1.05		4.43		382.00		-1485.00	
HRCB5	14.57	15.09	1.34	1.33	3.24	3.36	1.16	1.13	4.28	4.81	500.00	562.50	-1289.00	1389.50
	15.60		1.32		3.47		1.09		5.33		625.00		-1490.00	
HRCB6	15.42	14.47	1.31	1.32	3.43	3.22	1.13	1.13	5.26	4.82	680.00	612.50	-1621.00	1571.50
	13.52		1.33		3.01		1.13		4.38		545.00		-1522.00	

Based on Table 3 and Figure 7, similar effects of rubber were observed in stress at ultimate load in the rubberized and hybrid rubberized concrete through dropped results, in general, regarding the contents. On the other hand, the strain capacity of the rubberized beams was improved on average by 39.23% at 15% Cr from the stress-strain curve and 32.6 % from concrete strain gauges records. This is considered as an accurate measurement for confirmation. The results of this study were in line with the findings that were reported by Agampodi et al. [26]. Also, the gauges recorded the strain on the longitudinal reinforcement at tension zone during the loading. As displayed in Table 3, the strain of steel bars increased as the rubber content increased. However, the strain was less than 600 ×10^{-6} . This was expected according to what has been reported by previous findings. Therefore, it is confirmed that the strain in the steel bar at the tension zone will be less even though crumb rubber content increases [6]. In the hybrid rubberized concrete beam, the strain by gauges and stress-strain curve at concrete became lower between 1.32% to 2.66% and 19.13% to 30.34%, respectively in contrast with the rubberized concrete at the same rubber proportion (from 10% to15 %). In contrast, the stress became higher between 6.25% and 1.25 %. All these can be attributed to the changeable materials’ volume.



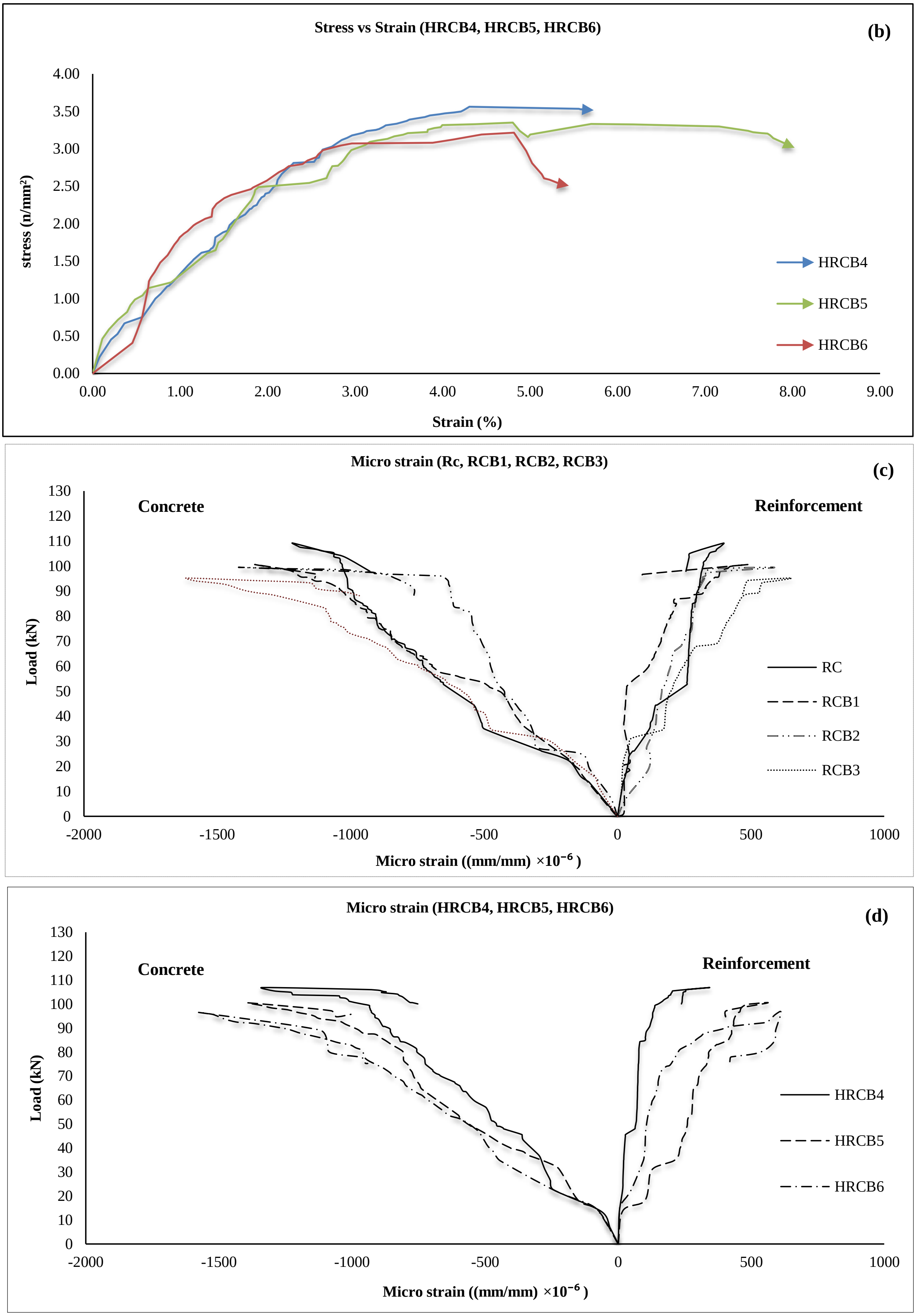


Figure 7. Stress-strain curve: a) Rubberized concrete, b) Hybrid rubberized concrete, and Strain gauges: c) Rubberized concrete, d) Hybrid rubberized concrete

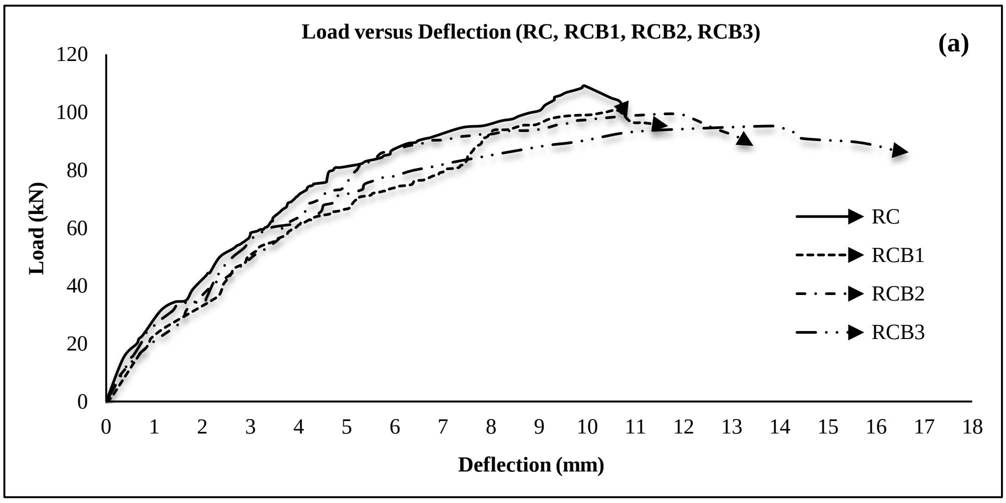
4.3. Characteristics of Load-deflection Behaviour

Table 4 shows the characteristics of mid-span deflection of beams, which were monitored by the naked eye and the calculation equations pertaining to the flexural test. As shown in Table 4, the first cracking load decreased as the percentage of Cr increased. For example, the inclusion of 10 % Cr in RCB1 has shown a reduction of an average of 8.7 % compared with control and decreased to 15.47% at 15%Cr. It was observed that in a hybrid beam, there was not a major improvement that caused the delay when the first cracking load emerged. Similarly, the trend was reported at deflection at first cracking. However, there was a minor effect on first cracking load.

Table 4. Results of Characteristics of Beams

Types of mix	specimens No.	Cracking Load, Pcr (KN)	Cracking Deflection, Δcr (mm)	yield Load, Pyield (KN)	Yield Deflection, Δyield (mm)	Ultimate Load, Pult (KN)	Ultimate Deflection, Δult (mm)	Total energy, Etotal (Toughness) (KN.mm)	Stiffness, K.(KN/m)	ductility index μ
RC	1	46.41	2.50	98.15	7.70	117.05	11.05	366.96	16.01	1.44
	2	45.97	2.12	88.32	5.80	101.40	8.84	319.51	16.48	1.52
	Average	46.19	2.31	93.23	6.75	109.22	9.95	343.24	16.25	1.47
RCB1	1	41.81	2.44	81.65	5.14	110.86	11.76	389.16	13.76	2.29
	2	41.71	2.40	82.77	5.47	90.25	9.53	345.36	14.12	1.74
	Average	41.76	2.42	82.21	5.31	100.55	10.65	367.26	13.94	2.01
RCB2	1	38.77	2.53	74.87	4.42	90.15	10.68	395.67	13.19	2.42
	2	39.41	2.38	85.60	5.38	108.78	13.06	409.28	14.05	2.43
	Average	39.09	2.46	80.23	4.90	99.46	11.87	402.48	13.62	2.42
RCB3	1	38.45	2.45	66.43	4.02	88.08	12.44	420.96	13.57	3.10
	2	38.88	2.48	83.41	4.91	102.48	15.24	430.80	12.65	3.10
	Average	38.66	2.47	74.92	4.46	95.28	13.84	425.88	13.11	3.10
HRCB 4	1	41.86	2.27	86.51	4.92	106.37	8.36	336.88	16.32	1.70
	2	41.92	2.09	87.84	4.75	107.39	8.86	326.22	14.29	1.87
	Average	41.89	2.18	87.17	4.84	106.88	8.61	331.55	15.31	1.78
HRCB 5	1	40.32	2.31	77.32	3.64	97.10	8.30	346.82	14.27	2.28
	2	39.62	2.17	87.74	4.74	104.02	10.65	366.72	15.60	2.25
	Average	39.97	2.24	82.53	4.19	100.56	9.48	356.77	14.93	2.26
HRCB 6	1	39.35	2.28	90.95	4.05	102.80	10.51	396.38	15.41	2.60
	2	39.47	2.26	77.75	4.16	90.17	8.76	336.63	12.53	2.10
	Average	39.41	2.27	84.35	4.11	96.48	9.63	366.51	13.97	2.35

Zemei et al. [27] reported that there was a significant effect of crumb rubber that was added in the reinforced concrete on the ultimate load and deflection rather than a minor effect on first cracking load. Figure 8 shows the ultimate load-deflection curves in an average for the rubberized and hybrid rubberized concrete. The addition of 15% crumb rubber aggregate as a replacement of fine aggregate seemed to increase the ultimate deflection to 39.09 % compared with the reinforcement of controlled concrete, whereas the ultimate load demonstrated a reduction occurred at 12.7% in contrast with control. Therefore, it is expected that there will be less strain in steel at tension by increasing the Cr content, which can be attributed to a decrease in the ultimate load [6]. Using 10% crumb rubber in the hybrid concrete beams decreased deflection and increased load at 19.15% and 6.29 %, respectively. These results can be attributed to the use of double-layered and rubber at the top. This was done in order to absorb the load and to minimize flexural strength loss.



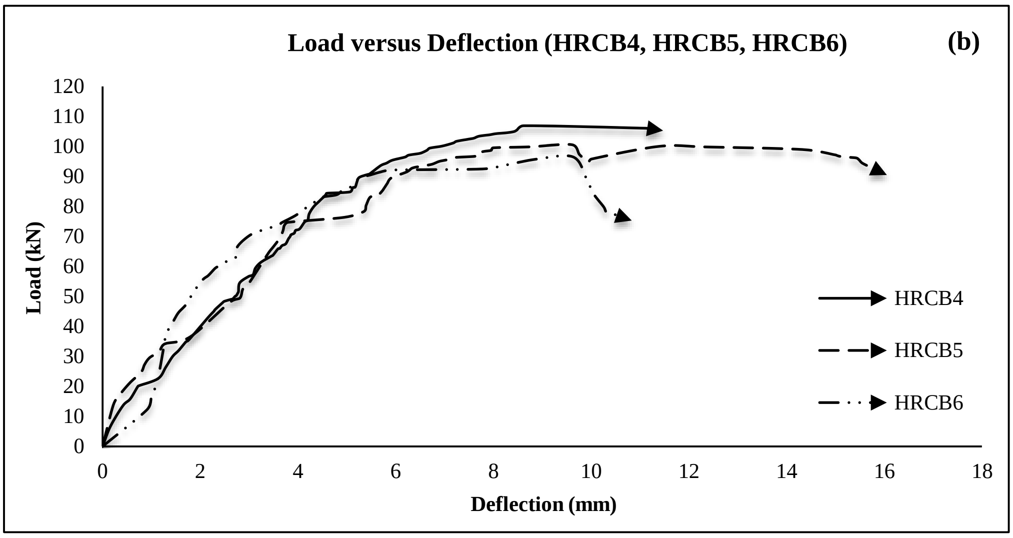


Figure 8. Load-deflections curve, a) Rubberized concrete, b) Hybrid rubberized concrete.

4.4. Toughness, Stiffness, and Ductility

The toughness (total energy) listed in Table 4 for each mixture was obtained by measuring the area enclosed by the deflection-curve of the reinforced concrete during the flexural test. Increasing the percentage of Cr has positively affected the ability of the beam to absorb the total energy up to failure and the deformability of the tested beams has increased. In this study, there was an increase in the deformability area for all the tested beams, which showed an increase in toughness. In the rubberized concrete beams, varying from 0% to 15% of crumb rubber percentage significantly increased toughness on average by 24.08%. Mohamed et al. [18] obtained high toughness by adding 5 to 15 % of crumb rubber content with 4.75 mm size into concrete and confirmed that the increase in Cr percentage beyond 15 % reduced toughness prior to failure. Other studies by the same authors confirmed these findings [6]. The hybrid concrete beams at failure absorbed a lower amount of total energy than in the rubberized concrete beams. Such findings of comparison on average, at 10% the rubber content for RCB1 reduced significantly on average from 367.26 to 331.55 for beams HRCB4 as shown in Figure 9. According to Guo et al. [28], this toughness increased when rubber content increased. Other researchers confirmed that the inclusion of crumb rubber in beams helped to increase the chances of the deformability, which improved the energy absorption [6].

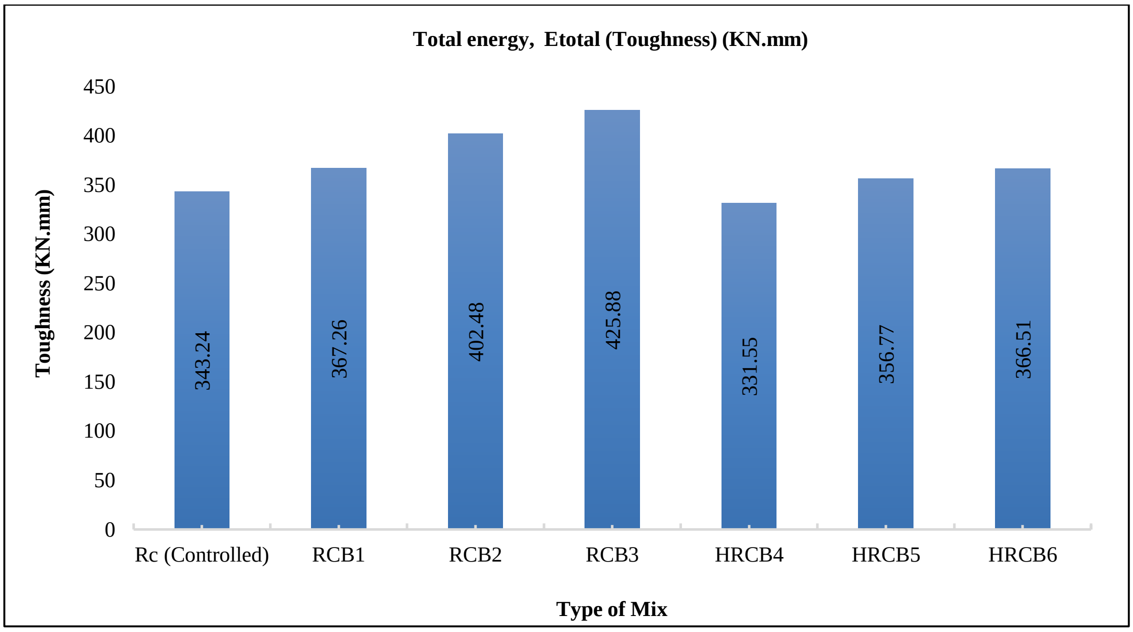


Figure 9. Total Energy (Toughness) results

In this study, the ductility index (μ) was used to assess the influence of crumb rubber on the deformability of all the tested beams. Generally, the inclusion of the crumb rubber in beams can contribute to improving strain and deformability and enhancing the duality in terms of increase [6, 29]. For instance, increasing the rubber from 0-15 % in the rubberized and hybrid rubberized concrete beams, which increased the ductility by 110.8 % and 35.2%, respectively.

Against this trend, when beams were more ductile and deform by increasing the rubber contents, this resulted in lower stiffness beams, e.g., RCB1 showed slightly lower average values at 13.11compared with RC at 16.25 KN/mm. On the other hand, hybrid concrete beams were considerably stiffer as clearly illustrated in Table 4.

4.5. Cracking Behaviour

Figure 11 (a, b) and Table 5 show the failure mode of the cracking (numbers, angle, widths, mix, and minim spacing) and of the tested beams. In the rubberized concrete beams, increasing the crumb rubber contents volume from 0% to 15% resulted in an increase in the number of cracking by 37% on average. On the other hand, the cracking numbers decremented in the hybrid beams by 16% on average in contrast with control. This is because of the modules of the elasticity of rubber aggregate that is lower than fine aggregate, which caused an increased number of cracking on the beams until crashing [6, 30]. In contrast, the widths appeared to be narrow by 39.3 % at 15% crumb rubber compared with control. However, it became narrow at 36% for the hybrid concrete beams as shown in Figure10. Mohamed K [6] reported an increase in the numbers of crack and decremented of the width of as Cr content increased.

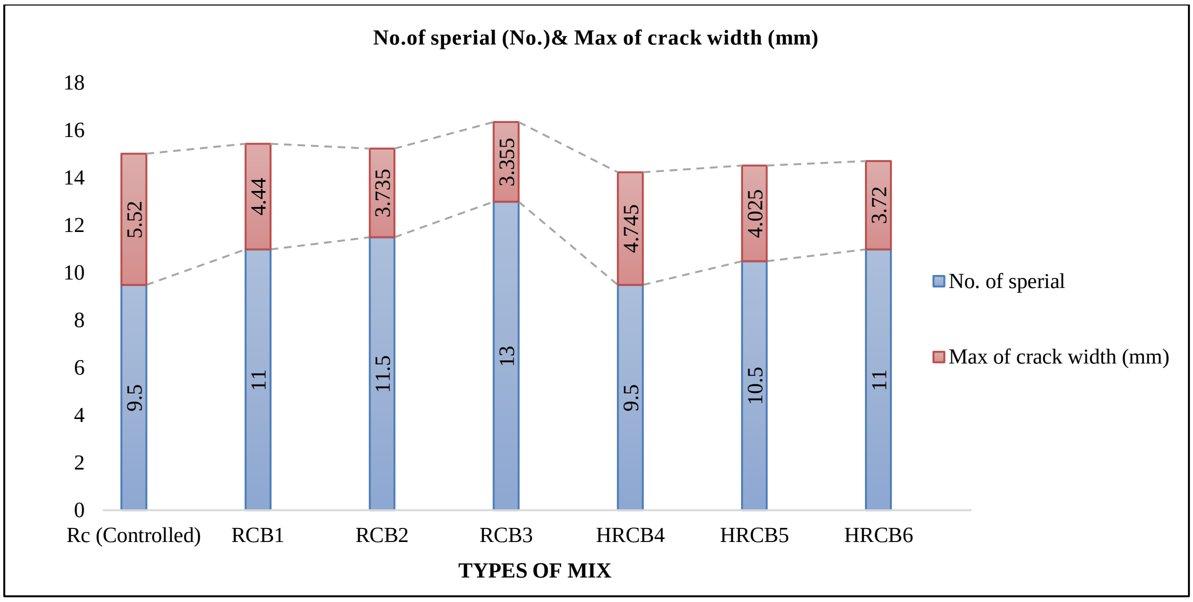
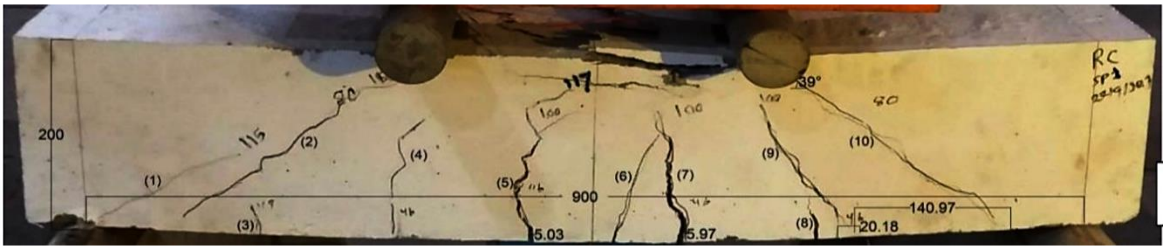


Figure 10. Crack Number and its Width Results

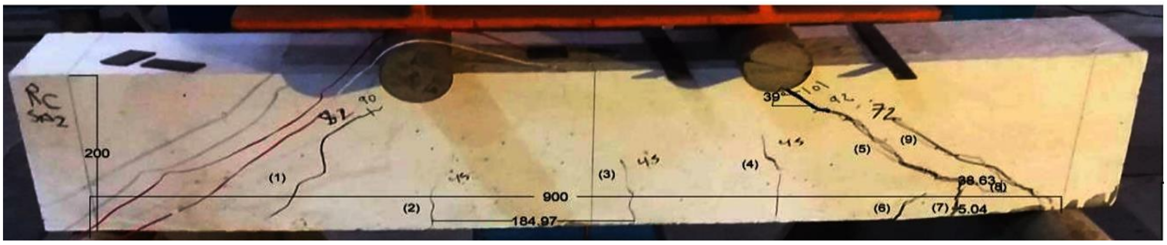
Table 5. Crack behaviour of beams in flexural

Type of Mix	No. of sperial	Average (mm)	Max of crack width (mm)	Average (mm)	Angle of crack at failure degree (deg. º)	Average (deg. º)	Minimum spacing (mm)	Average (mm)	Maximum spacing (mm)	Average (mm)
RC	10	9.5	6	5.52	39	39	20	29	141	163
	9		5.04		39		38		185	
RCB1	11	11	4.33	4.44	37	36	18	17	130	142
	11		4.55		35		16		154	
RCB2	11	11.5	3.74	3.74	34	35	15.69	14.57	155	133.5
	12		3.73		35		13.45		112	
RCB3	12	13	3.05	3.36	31	32	10	9.745	131	126
	14		3.66		32		9.49		121	
HRCB4	9	9.5	4.77	4.75	38	38	16	20.5	137	146
	10		4.72		38		25		155	
HRCB5	9	10.5	4.14	4.03	37	37	18	17.5	132	141.5
	12		3.91		37		17		151	
HRCB6	10	11	3.59	3.72	45	38	16	16.7	137	135.5
	12		3.85		30		17.4		134	

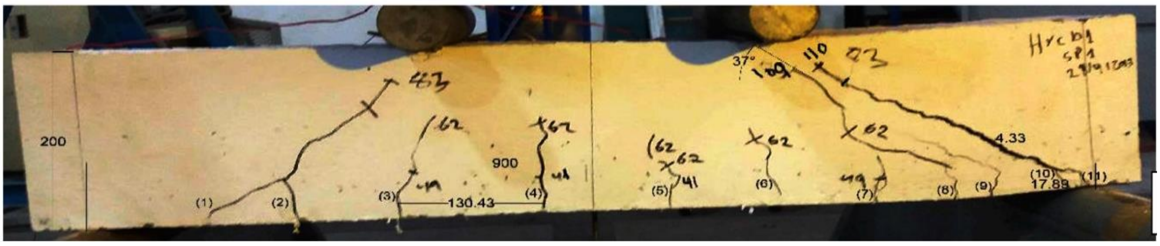
The crack propagation and its spacing for the rubberized and hybrid rubberized concrete of tested beams were measured. According to previous studies [6, 21, 29, 30], when the crumb rubber was added to conventional concrete, it caused more cracks. This indicates that the spacing between the two cracks will become lower whether for maximum or minimum spacing. For example, in the maximum spacing in RCB3 with the inclusion of 15% of crumb rubber decreased by an average of 23% compared with the conventional concrete (RC). Similarly, trends with minimum spacing were observed; the spacing decremented by 66 %. A hybrid, which has crumb rubber at the top of the tested beams will help to enhance crack behaviour and its spacing. Therefore, the maximum and minimum in HRCB4 were slightly enhanced by 3% and 18%, respectively. Further enhancement was observed in HRCB6 with 15% of fine aggregate replacement by crumb rubber aggregate at 8% and 7%, respectively. This has become clearer when it was compared with RCB3.



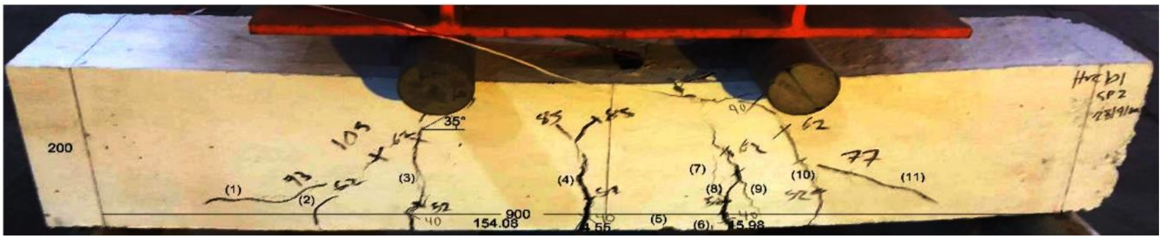
RC (1)



RC (2)

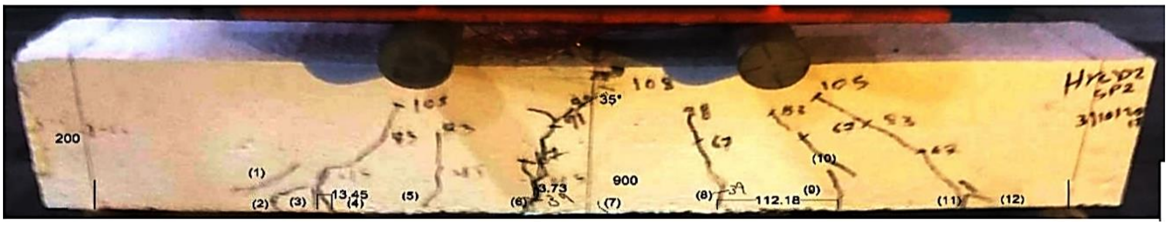


RCB1 (1)

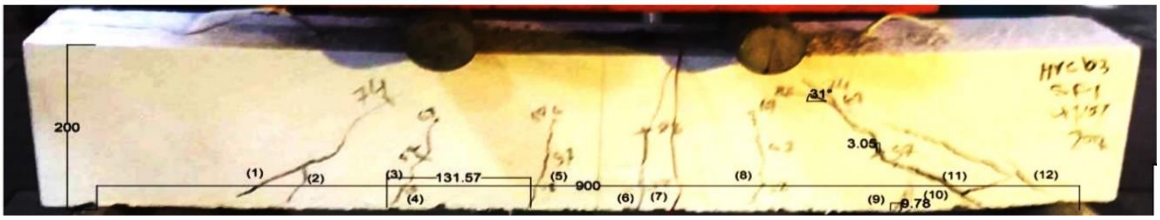


RCB1 (2)

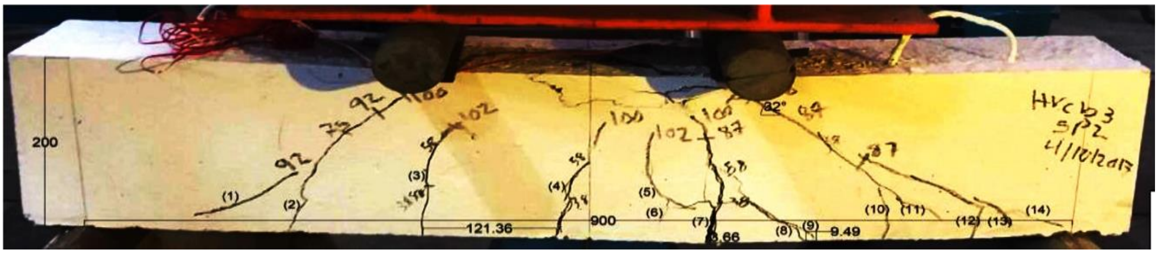
RCB2 (1)



RCB2 (2)

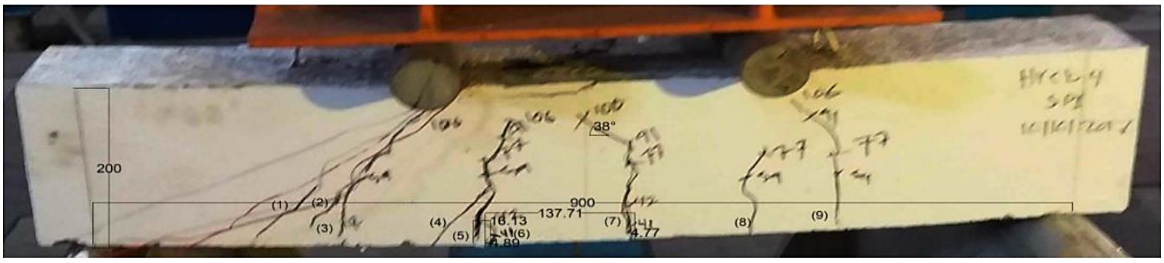


RCB3 (1)

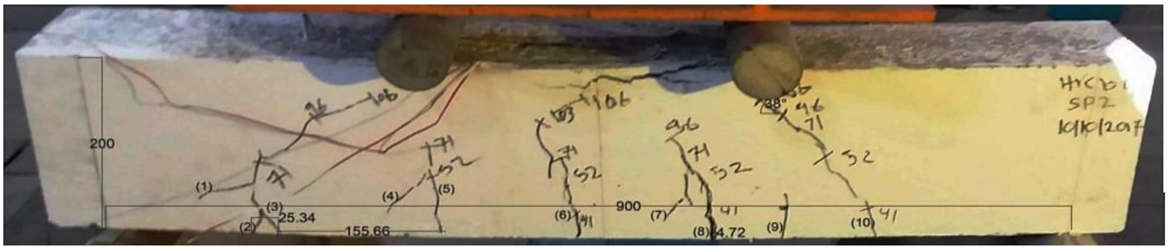


RCB3 (2)

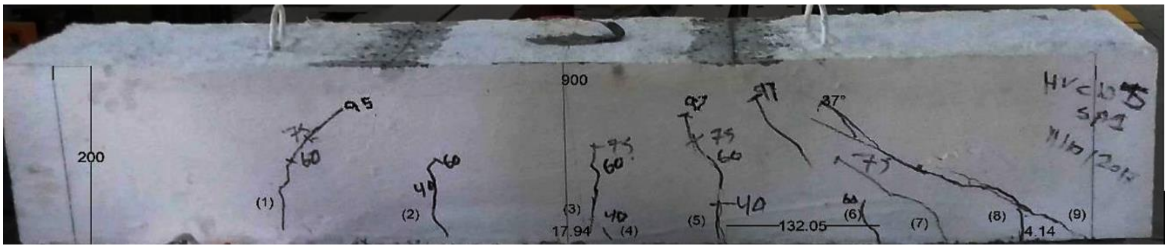
Figure 11. a) Crack behaviour of controlled and rubberized concrete



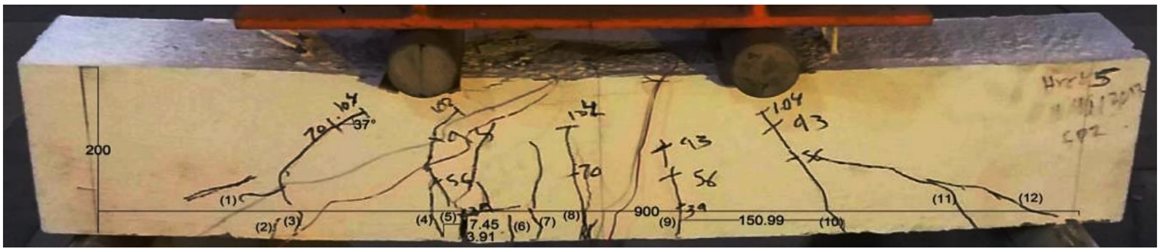
HRCB4 (1)



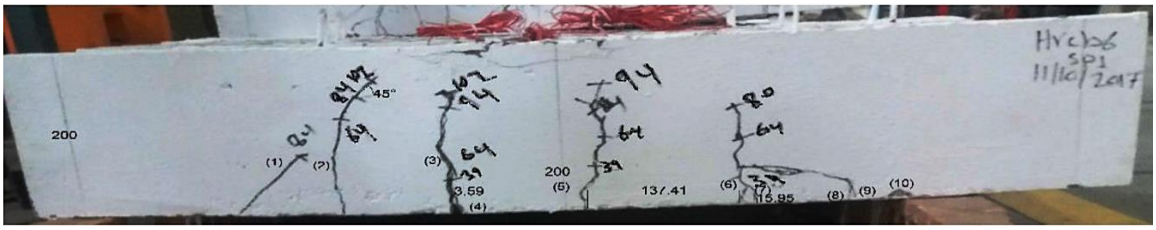
HRCB4 (2)



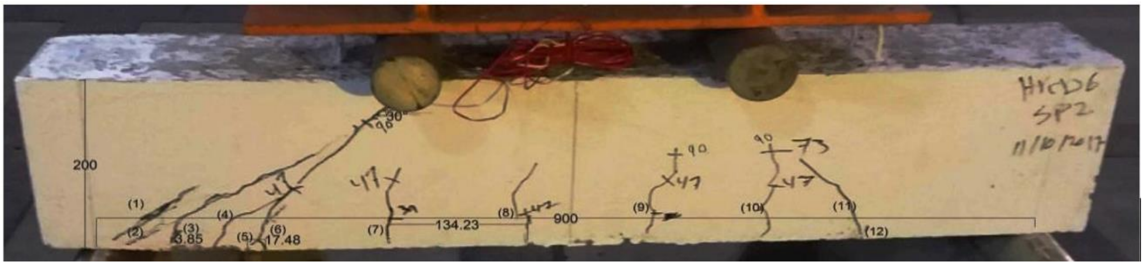
HRCB5 (1)



HRCB5 (2)



HRCB6 (1)



HRCB6 (2)

Figure 11. b) Crack behaviour of hybrid rubberized concrete beams

5. Conclusion

Fourteen rubberized reinforced concrete beams and hybrid reinforced concrete beams with double layers were investigated under flexural behaviour. The double-layer beam with a rubberized beam on the top was used with a ratio of 10%, 12.5%, and 15 % of sand volume replacement and the reinforcement concrete at the bottom. The fresh properties, failure mod, total energy (toughness), stiffness, and ultimate deflection, modulus of rupture, strain capacity and ductility index were studied for all the beams. Based on the experimental results, the following findings were obtained:

- The hybrid beam with double layers has shown better performance in contrast with the rubberized beam in the failure patterns (number of cracks, maximum, and minimum spacing), first cracking load, fresh properties, ultimate deflection load, stiffness, flexural strength, and stress.
- The rubberized beam has improved the ultimate deflection, ductility index, the strain that was obtained by both strains' gauges (concrete and steel bar), and the stress-strain curve in contrast with the hybrid beam.
- Better performance was achieved based on the results of this comparative study regarding the use of the hybrid beams for a new sustainable application in the construction industry.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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