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Combined Effect of Latex and Crumb Rubber on Mechanical Properties of Concrete for Railway Application

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Abstract: Crumb rubber incorporation is widely deemed to deteriorate the compressive strength of concrete. One of the dominant reasons for this strength reduction is known as the inferior bonding or weak interfacial transition zones (ITZ) between the crumb rubber and hardened cement paste. While Styrene-butadiene (SBR) latex is being used as a bonding agent in concrete manufacturing, the SBR latex usage holds the potential to compensate for the strength reduction from crumb rubber incorporation. This study focuses on evaluating the sole and combined effect of crumb rubber and SBR latex on the compressive strength, one optimum combination of latex modified rubberised mix (LMCRC) that had achieved 55.5 MPa of 28 days' characteristic strength was chosen to compare its impact resistance and stress-strain response to a plain concrete (PC) with similar characteristic strength. Experimental results showed both crumb rubber and SBR latex incorporation induced a compressive strength reduction in the concrete. The optimum latex modified rubberised mix with w/c of 0.32, crumb rubber replacement of 20kg/m^3, and 3% latex additives had outperformed the control mix with w/c ratio of 0.38 by 66.7% and 293% in the 400mm span impact test and 200mm span impact test, respectively. Besides, the latex modified rubberised mix showed higher Poisson's ratio, and higher compressive strain which indicates more ductile behaviour as compared to the plain concrete.

Keywords: Strength, impact resistance, strain, crumb rubber, SBR latex

1. Introduction

In recent years, the incorporation of crumb rubber in concrete manufacturing has gained extensive attention due to the great emphasis on sustainable development. The inclusion of crumb rubber in concrete making is not only deemed to be an environmental friendly alternative to replace the quarry aggregates, but at the same time helps to mitigate the environmental and health threats posed by the generation of waste tyres worldwide. Along with the rubber's unique properties in terms of hyper-plasticity and visco-elasticity, the existence of crumb rubber in concrete is also deemed to offer various mechanical benefits like improved ductility, impact resistance, damping effect, etc. [1]- [4]. These benefits in mechanical properties offered by crumb rubber concrete (CRC) make it a great alternative in various applications. In view of the decent impact resistance and damping properties, the CRC can be a great material choice for the construction of concrete sleepers, as railway sleepers are often exposed to high vibration and high impact environments [1], [5], [6]. Nonetheless, the application of CRC in concrete sleeper construction requires comprehensive research as CRC generally possesses low compressive strength, which is also an important parameter that needs to be considered. According to British Standard (BS EN 206-1) concrete used for constructing railway sleepers requires to achieve a minimum 28th days cube compressive strength of 55 MPa. Australian standard (AS 1085.14) also indicates at least 50 MPa of characteristic strength for concrete usage in railway sleepers manufacturing.

Many researchers had examined different combinations of crumb rubber usage in concrete manufacturing by modifying the percentage of replacement, sizes, types of rubber, and so on, trying to obtain the most optimum

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combination for different applications [7]- [10]. However, the study focuses on improving the interfacial transition zone (ITZ) surrounding the crumb rubber in rubberised concrete is relatively incomprehensive.

The ITZ generally refers to the thin layer of weaker cement matrix that formed in the vicinity of aggregates. These weaker cement matrixes usually possess larger crystalline products (calcium hydroxide and ettringite) with a more porous framework and high heterogeneity since the aggregates' surroundings tend to have a higher w/c ratio [11]. A higher w/c ratio with high water content and sufficient space then allows the unhindered growth of hydrates, while these porous hydrates products usually have a marginal effect on the mechanical strength [12]. In view of this, the improvement of ITZ's strength is very crucial to minimize the strength decrement caused by the porous and weak cement matrix. As the widely applied binding agent, the Styrene-Butadiene (SBR) latex offers the potential in mitigating the strength deterioration by introducing the bridging effect in the ITZ zone.

In this study, the sole and combined effects of crumb rubber and SBR latex on the compressive strength of concrete were examined. One latex modified crumb rubber concrete (LMCRC) with minimum characteristic strength of 55 MPa was selected from the mix designs to evaluate and compares its impact resistance and stress-strain response to a plain concrete (PC) with a similar characteristic strength.

2. Materials and Mix Proportions

In this study, the materials used were ordinary Portland cement (OPC), coarse and fine aggregates, crumb rubber, Styrene-Butadiene (SBR) latex, water, superplasticizer (SP), silica fume (SF), and gypsum capping powder. The concrete mix designs were evaluated based on two stages. The first stage involves the evaluation of sole (mix 1~7) and combined (mix 8~10) effects of crumb rubber and SBR latex in concrete. In the 2nd stage, a new PC with similar compressive strength (mix 11) was designed to study the performance of the LMCRC 3/20 (mix 10) in terms of impact resistance and stress-strain response.

2.1 Ordinary Portland Cement (OPC)

CEM I 52.5N ordinary Portland cement was used for this study. The cement was sieved through a 300μm sieve to remove lumps and stored in airtight containers prior to use.

2.2 Coarse and Fine Aggregates

Fine aggregates utilized in this study were washed river sand from a local provider with a specific gravity of 2.65 and a fineness modulus of 2.06. Locally sourced coarse aggregates with a specific gravity of 2.65 and fineness of 7.24 were used for this study. The coarse aggregate was sieved through a 20 mm sieve, a 10 mm sieve, and a 1.18 mm sieve to eliminate any particles that were retained on the 20 mm sieve as well as the particles that passed through the 1.18 mm sieve. The ratio of 20 mm coarse aggregates to 10 mm coarse aggregates was 2:1 for all concrete mix designs. To remove the moistures that initially existed within the pores, all aggregates were oven-dried for 24 hours at a temperature of (105±5) ºC, this is to ensure all the mixes can achieve consistent w/c ratio when added with water.

2.3 Water and Superplasticizer (SP)

The water used for this study is clean tap water at room temperature in compliance with ASTM 1602-06. All the concrete mixes were added with superplasticizer supplied by a local supplier as a high range water reducer to ensure high workability in the fresh mixes without affecting the strengths. The dosage of SP varied from 0.32% to 0.68% by weight of cement depending on the amount of water and SBR latex used for each concrete mix.

2.4 Silica Fume

Silica fume used in this study was aimed to enhance the compressive strength of the concrete. The silica fume was supplied by a local supplier, mainly consists of amorphous silica (> 85.0 %), crystalline silica (< 0.1 %), iron oxide (< 3.0 %), and calcium magnesium carbonate (> 1.1 %).

2.5 Gypsum Capping Powder

Gypsum capping material was used to construct the smooth and flat caps on the top and bottom of cylindrical specimens. The gypsum powder was supplied by a local supplier with a minimum compressive strength of 61.78 MPa at 35 minutes after mixing with water. The recommended w/c ratio was 0.155.

2.6 Mix Designs

The mix proportions for various mixes (PC, CRC, LMC, and LMCRC) are tabulated in Table 1.

Table 1 - Mix designs

Mix	Designation	Description	Unit Weight (kg/m^3)							
			Cement	Aggregate		Water	SBR Latex	Crumb Rubber	SF	SP
				Fine	Coarse					
1	PC 1	Plain concrete, 0.36 w/c	667	410	1107	240	-	-	40	3.34
2	CRC 20	20 kg/m^3 rubber, 0.36 w/c		362			-	20		
3	CRC 40	40 kg/m^3 rubber, 0.36 w/c		314			-	40		
4	CRC 60	60 kg/m^3 rubber, 0.36 w/c		266			-	60		
5	LMC 9	9% SBR latex, 0.27 w/c		410		180	60	-		
6	LMC 12	12% SBR latex, 0.27 w/c					80	-		
7	LMC 15	15% SBR latex, 0.27 w/c					100	-		
8	LMCRC 9/60	9% SBR latex, 60 kg/m^3 rubber, 0.27 w/c		266			60	60		
9	LMCRC 15/20	15% SBR latex, 20 kg/m^3 rubber, 0.27 w/c		362			100	20		
10	LMCRC 3/20	3% SBR latex, 20 kg/m^3 rubber, 0.32 w/c				210	20			4.54
11	PC 2	Plain concrete, 0.38 w/c		410		254	-	-		2.13

Note: The mix proportions are based on $1m^3$ concrete volume using the absolute method.

3. Specimens Preparation and Testing Methods

A total of 74 specimens were prepared for different tests in this study, namely 66 cubic specimens for cube compression test, 2 cylindrical specimens for cylinder compression test, and 6 prismatic specimens for repeated drop weight impact test.

3.1 Cube Compression Test

The cube compression tests were conducted based on BS EN 12390-3 to evaluate the compressive strength of different mixes. 100 mm cubic specimens were tested by using a universal compression machine at a loading rate of 6 kN/s.

3.2 Cylinder Compression Test

The cylinder compression tests were conducted in accordance with ASTM C469. The test aimed to examine the compressive stress-strain response of both PC 2 and LMCRC 3/20. Prior to the testing, the curved surface of each cylindrical specimen was ground with concrete-use sandpaper and attached with a two-elements polyester wire strain gauge (PLC-60-11) to obtain the strain readings. The PLC-60-11 strain gauge allows the capture of both axial (vertical) and transverse (horizontal) strain readings when connected to the TDS-530 data logger. Fig. 1 depicts the experimental setup of cylinder compression test. The cylindrical specimens were subjected to a constant compressive loading. For each cylindrical specimen, 3 cycles of experiments were conducted to the extent of around 40% of its ultimate strength before loading to confirm the consistency of strain readings.

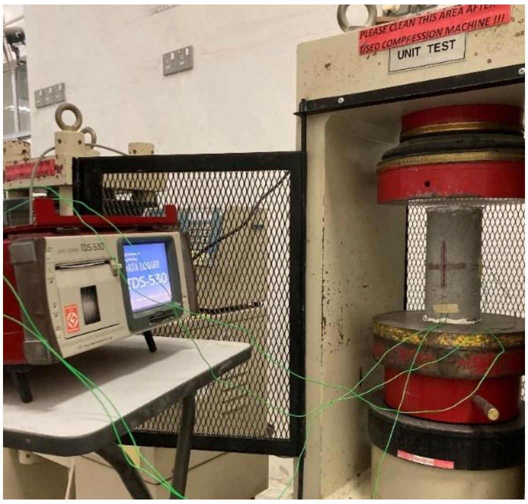

Fig. 1 - Experimental setup of cylinder compression test

3.3 Repeated Drop Weight Impact Test

The original ACI 544 repeated drop weight impact test naturally contains high discrepancies from the test results [12]. In this study, some modifications were made to improve the consistency of the test, including the introduction of line impact load, prismatic specimen, a notch on specimens, and different support conditions. These modifications have been proven efficient in improving the consistency of the repeated drop weight impact test in previous studies [12-13]. In this study, 2 impact tests were conducted to assess the impact resistance of the LMCRC 3/20 and PC2 mix. The first impact test was designed to drop a free-falling 2kg mass from the height of 200 mm on a 500 mm x 100 mm x 100 mm prismatic specimen with a 400 mm span length. 2 prismatic specimens that split into half after first impact test were then used in the second impact test, where a free-falling 2 kg mass from height of 300 mm was dropped on an approximate 250 mm x 100 mm x 100 mm prismatic specimen with a 200 mm span length. Since 2 samples can be generated from each 500 mm x 100 mm x 100 mm prismatic specimen, the average number of blows to induce failure was computed and presented in Table 2. Fig. 2 and Fig. 3 illustrate the schematic setup and actual setup for the 200 mm span impact test, respectively.

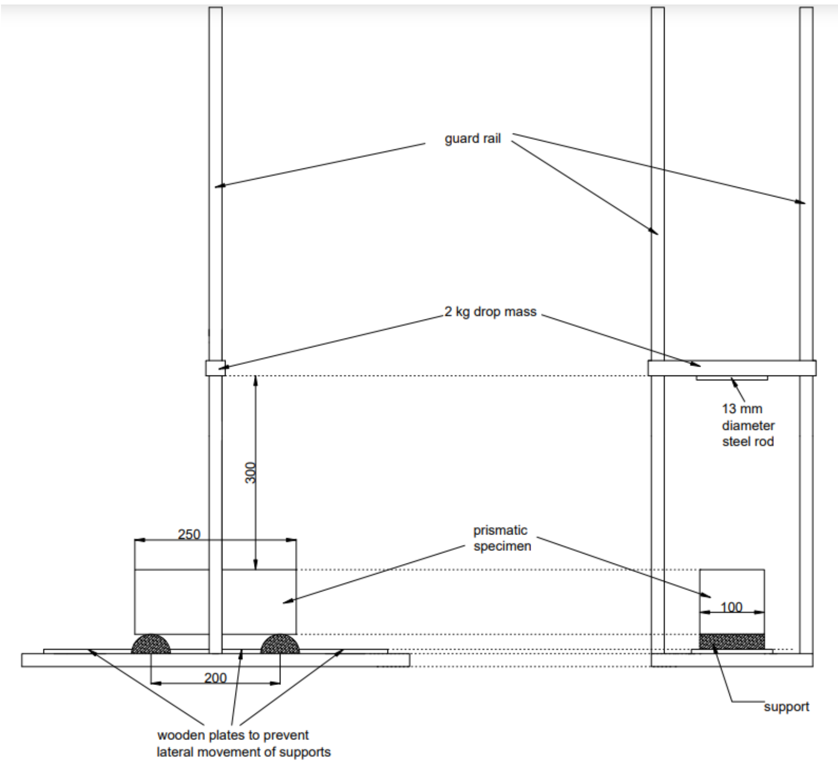

Fig. 2 - Schematic setup of repeated drop weight impact test (200 mm span)

Fig. 3 - Experimental setup of repeated impact drop weight test (200 mm span)

The 400 mm span impact test was basically a similar setup with adjusted drop height and span length. The number of blows needed to cause the ultimate crack/ failure as well as the impact energy (potential energy absorbed) were adopted to evaluate the impact resistance of each sample. The impact energy, E_{impact} was computed based on Eq. (1), where N is the number of blows to cause ultimate crack, m is the mass of drop weight, g is the gravitational acceleration = 9.81 m/s^2, and h is the height of drop weight.

$$E_{impact} = Nmgh \quad (1)$$

4. Results and Discussion

4.1 Compressive Strength

Fig.4 illustrates the 7th and 28th days compressive strength of PC, CRC, LMC and LMCRC. In general, the inclusion of solely crumb rubber or SBR latex decreased the compressive strength of the modified concrete, while the latter showed less significant effect. At 28th days of testing, the compressive strength reduction of CRC increased from 24.3% to 33% as the rubber replacement increased from 20 kg/m^3 to 60 kg/m^3. This phenomenon is expected since crumb rubber offers weak bonding strength, carbon black, as well as lower hardness and density compared to fine aggregates being replaced. On the other hand, the inclusion of SBR latex from 9% to 15 % by weight of cement as additives had induced a 28th days compressive strength reduction from 22.1% to 26%. This can be attributed to the formation of latex film with low compressive strength that is also deemed to hinder the hydration process of cement, especially at the early age. Despite the strength deterioration caused by SBR latex addition, all the LMC showed higher percentage of 7th to 28th days strength growth (> 20%) compared to the CRC and PC. This can be due to the latex film requires a longer time period to develop in thickness and fill up the fine void among the cement matrixes and subsequently increase the concrete strength. A similar phenomenon can be observed in the finding of Kapil et al. [14], the researchers investigated LMC by adding up to 20% of SBR latex to the normal concrete and found negative compressive strength development at 7th days and 14th days of testing but positive strength gain at 28th days of testing. On the other hand, Moodi et al. [15] recorded positive compressive strength gain in LMC only at 90th days of testing.

By combining the designs from the trial mix in stage one (CRC and LMC), the LMCRC was unable to achieve the targeted compressive strength of 55 MPa at 28th days. Both LMCRC 9/60 and LMCRC 15/20 only achieved 28th days compressive strength of 39.6 MPa and 49.6 MPa, respectively. This indicates that the inclusion of high content of SBR latex could not help in mitigating the compressive strength reduction caused by the crumb rubber. However, it can be noticed that the strength deterioration caused by the addition of SBR latex in LMCRC is relatively mild when compared to LMC, which suggests the formation of latex film might have performed its role as a bridging agent among the crumb rubbers and cement paste and helped to improve the strength of ITZ, yet the bridging effect is still less dominant when compared to the strength deterioration caused by the latex film itself. As both LMCRC 9/60 and LMCRC 15/20 did not achieve the target strength, this prompted the necessity of making other adjustments like lowering the water to cement ratio, increasing the cement content, etc. In this study, the water to cement ratio of the finalised LMCRC needs to be adjusted to 0.32 (LMCRC 3/20) in order to reach 28th days strength of 55.5 MPa. Such a low w/c ratio had extenuated the strength deterioration by introducing the hard inclusion of cement particles that are deemed to offer strengthening properties in concrete. Concurrently, the latex content was also lowered to 3% by weight of cement to moderate the negative strength effect brought by the formation of latex film.

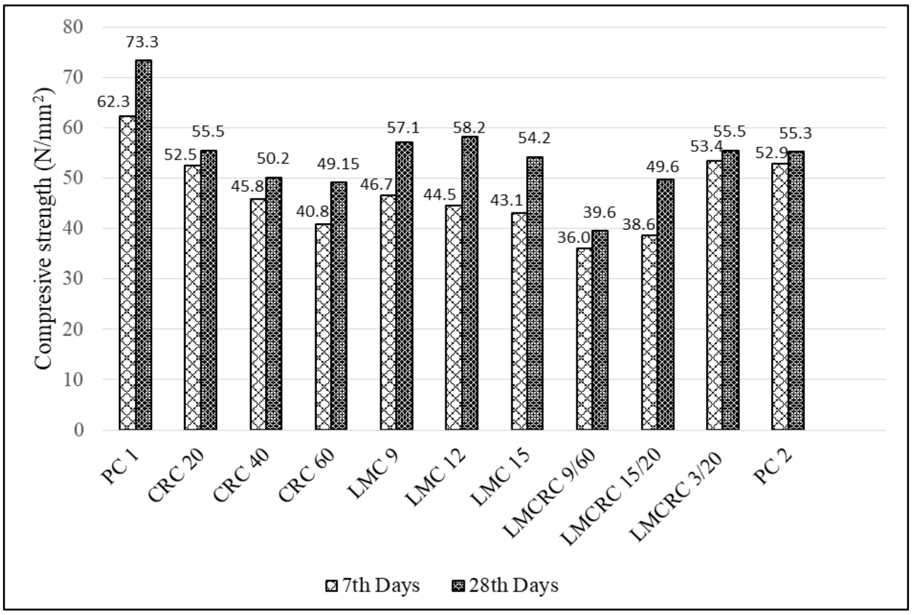

Fig. 4 - Compressive strength of various mixes

4.2 Compressive Stress-Average Strain Response

Fig. 5 and Fig. 6 show the cylindrical compressive stress-strain response of PC2 and LMCRC 3/20, respectively. The ultimate cylindrical compressive strength of PC2 and LMCRC 3/20 was 50.9 MPa and 48.4 MPa, respectively. In comparison with the characteristic strength, the cylindrical compressive strength of PC2 and LMCRC 3/20 was 7.9 % and 12.8 % lower, respectively. This phenomenon conformed to European standard (EN 1992-1-1) with some discrepancies, which stated cylindrical compressive strength should be 20 % lower than cube compressive strength. The discrepancies still deemed as acceptable when expected variation in experimental tests due to minor difference from different batches of mix was taken into consideration. Generally, LMCRC 3/20 exhibited more deformation in both transverse and axial directions as compared to the PC2. At 40% of the ultimate strength, the LMCRC 3/20 possessed lower stiffness as the elastic modulus of this mix design only reached 29 GPa, while the elastic modulus of PC2 had achieved 36.8 GPa. This suggested LMCRC should possess better impact resistance than the PC at similar characteristic strength but at the same time also bear the downside of higher deformation when subjected to compressive loading. Concurrently, LMCRC 3/20 also indicated a higher Poison's ratio (0.15) in comparison with PC 2 (0.10), which also suggested the high ductility from both crumb rubber and latex film increased the Poisson's ratio of the concrete.

4.3 Impact Resistance

By considering the naturally high discrepancy that can occur in the test, the coefficient of variation (COV) calculated for all 4 combinations of tests was relatively low, starting from the lowest of 24.6% (PC 2 with 200mm span) to the highest recorded at 36.4% (LMCRC 3/20 with 200mm span). This denotes the modifications to test setup improved the consistency of the impact test. Among the tested samples, results from 2 particular specimens were excluded from the calculation of average number of blows to cause ultimate crack and the coefficient of variance due to unexpected crack propagation, in which the specimens cracked away from the notch upon failure. These unexpected crack propagations indicated there might be existence of soft mortar or weak spot near the mid span of specimens. The samples rejected from evaluations were LMCRC specimens tested by 200 mm span impact test. Fig. 7 depict both accepted and rejected failure patterns, respectively.

According to Table 2, the LMCRC also showed better impact resistance compared to the control specimens regardless of the span length tested (200mm and 400mm). The average impact resistance of LMCRC outweighed the control specimens by 66.7 %. In 200 mm span impact test, the discrepancy was more significant, in which the LMCRC outperformed the PC by 293%. The improvement of impact resistance in LMCRC can be attributed to the hyper-elastic properties of the crumb rubber and latex film that allow it to exhibit large elastic strain which is recoverable, this means more deformations are allowed in the LMCRC 3/20 than PC2 when subjected to similar impact loadings. The larger deformation thus induced a lesser impact force since the impact force is inversely proportional to the distance travelled right after the collision happens. Additionally, crumb rubber also possesses great energy storage capacity; its visco-elastic properties allow it to return to the initial shape after large deformation while absorbing large amount of shock energy.

Despite same mix designs being tested, it is quite noticeable that the 200 mm span test magnified the distinct performance between PC and LMCRC in terms of impact resistance. Similar phenomenon also can be observed in the studies of Barr and Bouamrata [12], the researchers examined the impact resistance difference between different samples with various fibre content through a series of repeated drop weight impact tests by modifying the drop height, span length, drop weight, and notch depth of the test. According to Barr and Bouamrata [12], the difference of impact resistance was relatively low (around 200%) when the number of blows to failure was small (2-14), whereas the difference in impact resistance among similar sets of mix designs was boosted up to 564 % when the number of blows to failure was high (12-54). The similar outputs were found in the current study.

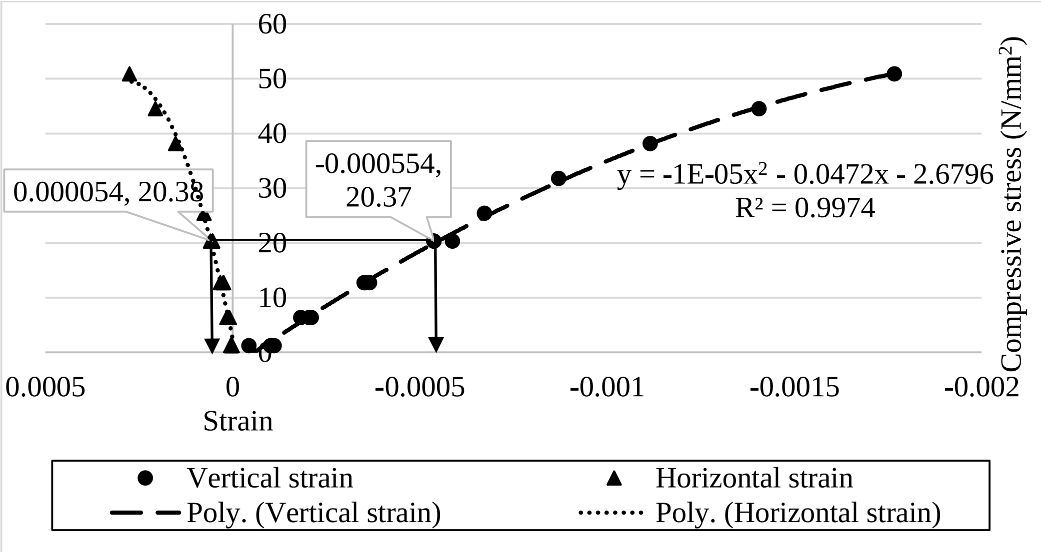

Fig. 1 - Compressive stress-strain curve of PC2

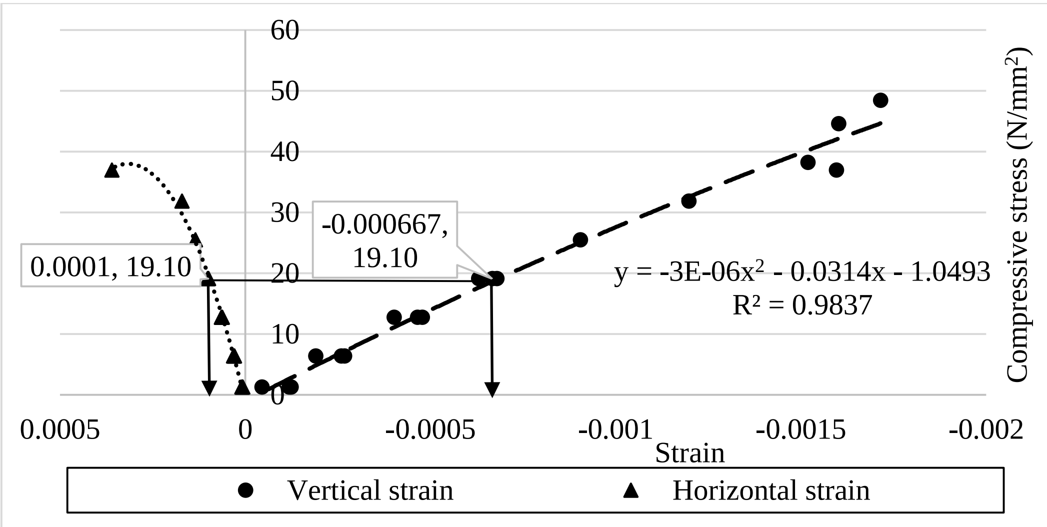

Fig. 6 - Compressive stress-strain curve of LMCRC 3/20

(a) (b)

Fig. 7 - Failure patterns of 200 mm span specimens (a) accepted; (b) rejected Table 1. Impact resistance of various mixes

Designation	Mix Reference No	400 mm Span (Drop Height 200mm)		200 mm Span (Drop Height 300mm)	
		No of Blows	Impact Energy (J)	Average No of Blows	Impact energy (J)
PC 2	1	4	15.7	7.5	44.1
	2	3	11.8	6.5	38.3
	3	7	27.5	9	53.0
	Coefficient of variance (%)	36.4		24.6	
LMCRC 3/20	4	12	47.1	29	170.7
	5	8	31.4	31.5	185.4
	6	5	19.6	Discarded	-
	Coefficient of variance (%)	34.4		32.2	

Note: Discarded raw data refer to unexpected crack propagation and were not used for calculation.

5. Conclusion

The objectives of this study were mainly to study the sole and combined effects of incorporation of crumb rubber and SBR latex in terms of compressive strength of concrete. The optimum LMCRC with minimum 28th days compressive strength of 55MPa was used to compare its impact resistance and compressive stress-strain response with another PC with similar 28th days compressive strength. Several conclusions can be drawn as follows:

- Both crumb rubber and SBR latex induced negative compressive strength growth in concrete. The combination of crumb rubber and SBR latex induced a negative strength growth in concrete but the effect was relatively moderate, which probably due to the bonding effect brought by the formation of latex film.
- LMCRC 3/20 displayed higher transverse and axial deformation in comparison with PC2. The elastic modulus of LMCRC 3/20 was lower than PC2's. Additionally, LMCRC 3/20 also possessed a higher Poisson's ratio value compared to that of PC2.
- LMCRC 3/20 showed better impact resistance than the PC2 contributed by the ductile behavior offered by crumb rubber and latex film. The repeated drop weight impact test with 200 mm span further magnified the advantage of LMCRC 3/20 against PC2 in terms of impact resistance.

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