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Effect of Replacement of Sand by Waste Fine Crumb Rubber on Concrete Beam Subject to Impact Load: Experiment and Simulation

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Abstract

In this study, the effect of partial replacement of sand by waste fine crumb rubber on the performance of hybrid structure concrete beam (double layer beam with rubberized top and normal bottom) under impact loading were investigated experimentally and numerically. Rubberized concrete materials were prepared by partial substitution (2.5%, 5% and 7.5%replacements by volume) of sand by waste fine crumb rubber of particle size 0.4–0.8 mm. Two types of specimens (size 100 mm ×100 mm × 500mm) namely, plain concrete and hybrid concrete were loaded to failure in a drop-weight impact machine by subjecting to 30 N weights from a height of 400mm, and similar specimens were used for the static load test. The dynamic beam behavior was analyzed numerically using the finite-element method (FEM) based LUSAS V.14 software.

In general, the results reveal that the impact bending load in the hybrid beam increases with increase in the percentage of sand replacement by fine crumb rubber, while the static peak bending load always decreases.

Keywords: Hybrid; Impact behavior; Finite element analysis (FEA); Mechanical testing.

1.0 Introduction

Cement consumption is increasing day by day as the main constituent of concrete which is the most widely used construction material. Increased use of cement poses environmental challenge as 5% of the global anthropogenic CO2 emission is originated from cement production [1]. Alongside this, there is increased generation of waste rubber which also has adverse ecological effects, due to its health hazards and difficulty for land filling. The high cost of disposal and requirement of large landfill area resulted in random and illegal dumping of waste rubber [2]. As a promising solution to the aforementioned problems, the idea of adding waste crumb rubber to concrete as sand replacement has recently gained attraction, as it improves the flexibility and ductility of concrete [3,4]. Substantial works were reported on the use of polymers such as tire rubber as a replacement for cement, sand or aggregates in concrete mixtures [3-13]; these studies revealed that the addition of rubber to concrete enhanced the elastic behavior, while reducing the compressive strength.

Khaloo et al. [5] studied the toughness of concrete specimens containing tire chips, crumb rubber, and a combination of tire chips and crumb rubber, which replaced 12.5%, 25%, 37.5%, and 50% of the total volume of mineral aggregates. Toughness was enhanced by the additions of all the aforementioned types of rubber, and the maximum toughness index was found with 25% replacement beyond which the toughness decreased. Al-Tayeb et al. [6] observed that the replacement of cement and sand with rubber powder or crumb rubber in concrete enhanced impact resistance. In this study the effect of partial replacement of sand by 2.5%, 5% and 7.5% of waste fine rubber on the load-displacement behavior and fracture energy of plain concrete and the hybrid concrete (double layer beam with rubberized top and normal bottom) subjected to impact load were investigated experimentally. As far as the authors are aware, the analysis of hybrid rubberized-normal structure for this type of rubberized concrete (with 2.5%, 5% and fine crumb rubber 0.4–0.8 mm particle size) has not been reported so far. For each case, three beams of size 100 mm ×100 mm × 500mm were loaded to failure in a drop-weight impact machine which facilitated dropping 30N weight from 400mm height, and similar specimens were tested under static load. The tup and bending load histories, and load-displacement behavior were analyzed for the normal and hybrid concrete beams. The results were compared with those under static load and those obtained by numerical simulations using Lusas program.

2.0 Materials and methods

2.1. Materials

Concrete with 50MPa compressive strength was prepared as the control mix. The maximum coarse aggregate size was 10 mm, and natural sand was used as fine aggregate. The specific gravities of coarse aggregates and sand were 2.65and 2.66 respectively. Concrete mix was prepared with replacements of sand volume by2.5%, 5% and 7.5% (designated as Fr2.5%, Fr5%, and Fr7.5% respectively)with waste fine crumb rubber of particle size 0.2–0.8 mm. Figure 1 shows the images of fine crumb rubber sample (relative density, 0.53) used in the present study.

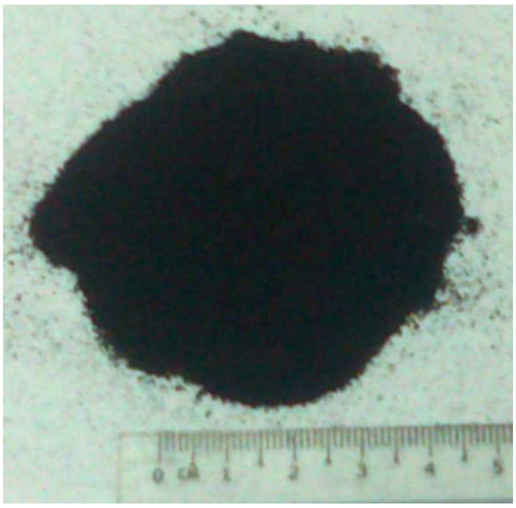

Figure 1. Image of the rubber powder sample.

For the compression and modulus of elasticity tests, three cylinders of height 300mm and diameter 150 mm were used for each type, according to ASTM C 39 [14] and ASTM C 469 [15], and three cylinders of height 160mm and diameter 100 mm were used for split-tensile, according to ASTM C 496 [16]. The specimens for three-point static and impact flexural loading tests were 100 mm wide, 100 mm deep and 500 mm long, with a loaded span of 400 mm. All specimens were cured in water for 28 days in accordance with ASTM C 192[17].

2.2. Experimental set-up and procedure

The three-point static flexural strength tests were performed according to ASTM C78 [18].

Impact tests were conducted on an instrumented falling-weight impact machine as in Figure 2; the machine facilitated dropping 4 kg hammer from 400mm drop heights. The impact load history during the test was measured using piezo-electric load cell of 50 kN capacity. The specimens were supported by two steel cylinders of 10 mm diameter. The specimen acceleration during impact was recorded by accelerometer with a range of ±2500g (g is gravitational acceleration) and Sensitivity 2.5 mV/g. Data from the load cell and the accelerometer were recorded at 0.2ms intervals using a PC-based data acquisition system.

Figure 2. The experimental impact flexural test rig.

The tup load, Ptat the mid-span of the beam recorded by the load cell is the sum of inertial load (Pi) and bending load (Pb) acting at the center [19-22]. So:

$$Pb = Pt - Pi \tag{1}$$

where Pi for linear distribution of accelerations along the beam is uniform, and expressed by:

$$Pi = \rho A a [L/3 + (8/3) \times (ov3/L2)] \tag{2}$$

where ρ: mass density of concrete; A: area of cross-section of the beam; a: acceleration at the center; L: span of the test beam; and ov: length of the overhang.

The displacement histories at the load-point can be obtained by double integrating the acceleration history a(t):

$$d(t) = \int_0^t \int_0^t a(t)dt \tag{3}$$

The fracture energy was calculated as the area under impact bending load versus displacement curve [19-22].

2.3 Finite element model

In order to simulate the behavior of rubberized concrete beams subjected to the impact load, LUSAS V.14 was used. The concrete beam was assumed to be built up with hexahedron elements [23].

The tup load curve obtained from experiment was used to define the load at the location Pt(x=250mm, y=100mm, z=50mm), and each beam was supported widthwise with cylindrical supports at locations x =50mm (support 1) and x =350mm (support 2).Elasto-plastic material was used to model both plain and rubberized concrete structures. To choose the appropriate number of elements and mesh size, a number of trials were made.

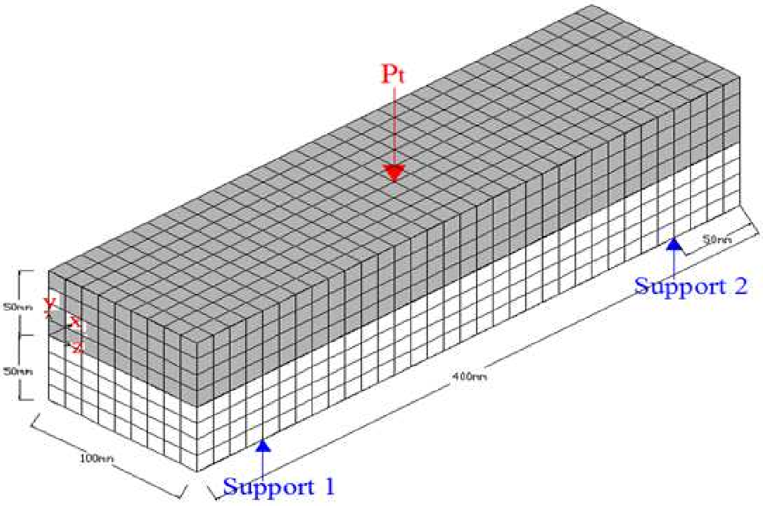

Figure 3. Finite element model for the beam.

Explicit (central difference) nonlinear dynamic scheme was used to determine the acceleration and thus the velocity and displacement increments for each time step [24]. The damping ratiofor first circular and second circular frequencies is assumed as 5% [25].

3.0 Results and discussion

3.1 Experimental results

The results of compressive stress and modulus of elasticity are given in Table 1. It is observed that, the average compressive stress of the plain concrete in 28 days is 46MPa. As the cement volume is decreased with proportional addition of rubber powder,the compressive stress reduces by 11, 19 and 20% with 2.5%, 5% and 7.5% of volumes respectively. The elastic modulus was also found to decrease by3, 6 and 13% respectively compared with the plain concrete. Similar observations were also reported by Khaloo et al. [5].

Table 1: Compressive strength and modulus of elasticity

Concrete type	Average compressive stress (MPa)	Average elastic modulus (kN/mm^2)
Plain	46	29
Fr2.5%	41	28
Fr 5%	37	27
Fr 7.5%	32	25

The normal and hybrid rubberized-normal beams fail in bending mode and there was no delamination of the material during the hybrid beam test. Figure 4 depicts the histories of tup load, inertial load and bending load for plain concrete and the three types of hybrid rubberized-normal concrete structure. The results show that both the inertial load and bending load increase significantly with increase in the percentage of sand replacement by fine crumb rubber. The inertial load increases because addition of rubber increases the flexibility of the composite mix. The increase in tup and bending loads is due to the fact that, as the rubberized top which is directly subjected to the impact load, has enhanced ability to absorb impact energy [6]. At the same time, since the plain concrete has better tensile strength than rubberized concrete, the ability of plain bottom to resist the tensile stress acting on it as a result of the impact load on the hybrid structure, is quite obvious. Thus the present hybrid structure exploits the important positive features of normal concrete beams, thereby maximizing its performance under impact load.

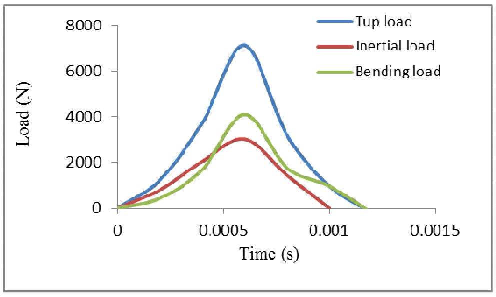

Fig. 4a: Plain concrete.

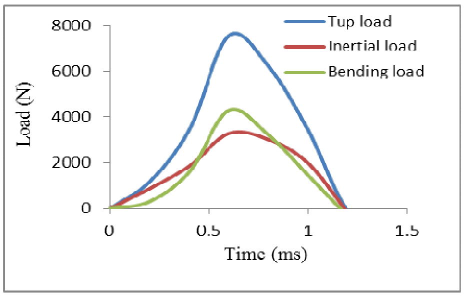

Fig. 4b: Fr2.5%.

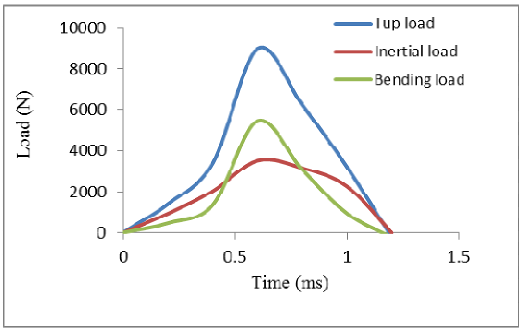

Fig. 4c: Fr5%.

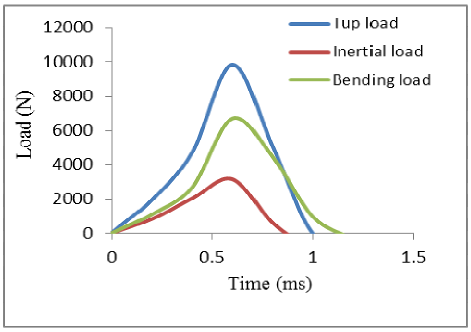

Fig. 4d: Fr7.5%.

Figure 4. Variations in Tup, inertial, and binding loads with time.

Figure 5 shows the calculated impact bending load against deflection for the plain and the hybrid rubberized-normal concrete structure. In this article, the fracture energy is defined as the area under impact bending load vs. displacement curve [19-22]. Table 2 summarizes the fracture energies for the plain and hybrid concrete beams. The dynamic fracture energy is higher than static fracture energy as also observed in the previous studies [19-22, 26]. The fracture energy of the plain concrete under impact load is 1.35 Nm. As the sand is replaced by 7.5% volume of fine crumb rubber, the fracture energyis increased by 170%.

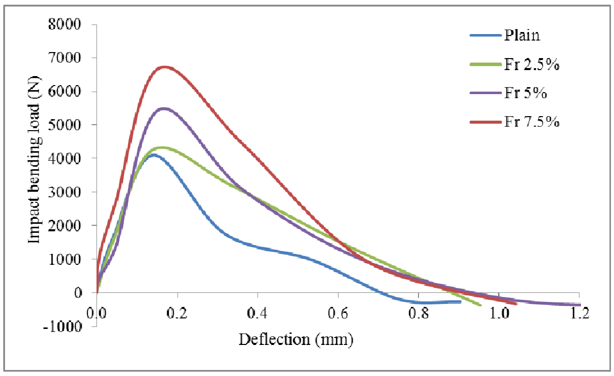

Figure 5. Impact bending load against deflection

3.2 Comparison of dynamic and static test results

Table 2 shows the comparison between the results obtained from static bending and impact bending tests. Generally the static peak bending load is less than the impact peak bending load; this is consistent with the published works [19-22, 26]. It is also observed that that the ratio between dynamic and static peak bending loads increases inthe hybrid rubberized-normal concrete structure. This is because the impact bending load increases with sand replacement by fine crumb rubber while it is reverse for the static bending load. Addition of rubber to concrete decreases its strength under static load but the ability of rubber to absorb dynamic energy enhances the strength of concrete under impact load.

Table 2: Comparison of experimental static and impact bending

Concrete mixes	Static test		Impact test	
	Peak bending load (N)	Fracture energy (Nm)	Peak bending load (N)	Fracture energy (Nm)
Plain	3944	0.53	3931	1.35
Fr2.5%	3637	0.56	4282	1.79
Fr 5.0%	3439	0.59	5463	2.03
Fr7.5%	3129	0.61	6702	2.68

3.3 Validation of FE simulation

The predicted impact load vs. displacement behaviors for plain concrete and hybrid structure beams were compared with the respective experimental results, as illustrated in figure 8 which demonstrate the strength of the proposed model in handling the problem.

The failure in all the beams predicted by the FE model is of bending mode which is consistent with the experimental results.The predicted impact load vs. displacement behaviors for plain concrete and rubberized concretes were compared with the respective experimental results, as illustrated in Figure 6 which demonstrate the strength of the proposed model in handling the problem. Figure 6a shows that at the end of impact response of the plain concrete, the predicted and experimental displacements are 0.9mm and 0.7mm respectively. The predicted and experimental displacements still closed with sand replacement by fine crumb rubber as shown in Fig 6b to Fig 6c. Thus it can be deduced that the proposed FEM model is excellent in handling the problem under investigation.

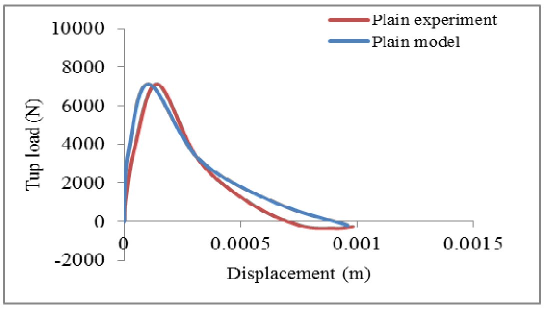

Fig. 6a: Plain concrete.

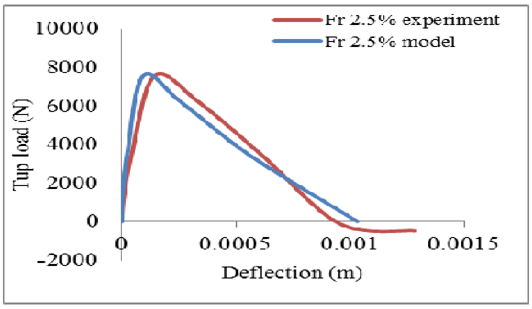

Fig. 6b: Fr2.5%.

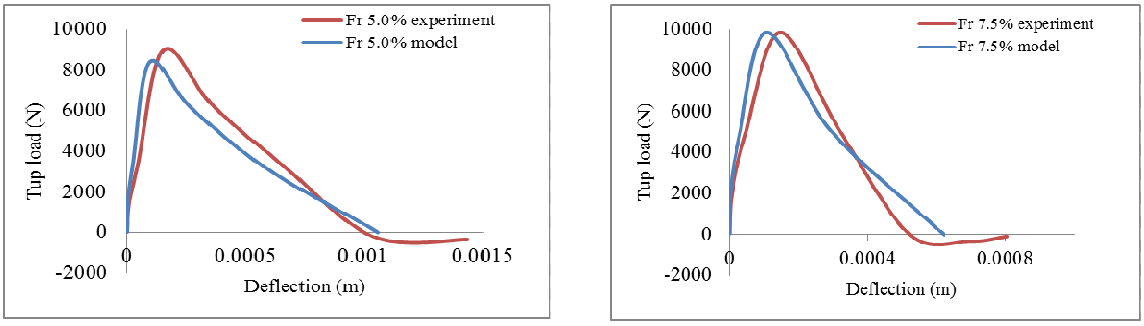

Fig. 6c: Fr5%.

Fig. 6d: Fr7.5%.

Figure 6. Variations in Tup, inertial, and binding loads with time.

4.0 Conclusion

It has been experimentally demonstrated that the impact tup, inertial load and bending load of hybrid structure increased with the increase in the percentage of sand replacement by fine crumb rubber; however the static peak bending load always decreased. Accelerometer could be used successfully to measure both the displacement and inertial loading effects in the instrumented impact tests. The impact bending energies were larger than the static energies, in all the cases. On the other hand the fracture energy increased with the increase in percentage of sand replacement. It was also proved that the proposed finite FEM modeling and simulation by using LUSAS could excellently predict the load against displacement behavior of both plain and rubberized concretes. The present numerical technique would be a promising breakthrough in this area, as it solves most of the issues associated with the tedious, risky and costly experimental procedures involved, and provide realistic and accurate predictions.

5.0 Recommendations

Extended work is underway, to analyze and investigate the behavior of rubberized concrete under torsions, compressions, tensions, with static and dynamic loads by using finite element method, boundary element method and difference element method for modeling and simulation of this concrete structure under torsions load.

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