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ORIGINAL CONTRIBUTION

Behaviour of Fibre-Reinforced Rubcrete Beams Subjected to Impact Loading

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Abstract Impact resistance of a material is of utmost significance in many essential structural applications. But, concrete is weak in withstanding impact/collision/blast loads. Addition of crumb rubber as a replacement of mineral aggregates has yielded a material which has high impact resistance and is termed as rubcrete. It has been observed that 0–20% replacement of fine aggregates with crumb rubber produces rubcrete with high energy absorption capacity. But, rubcrete is usually associated with a reduction in strength. Pretreatment of crumb rubber particles and grading them in the same proportion as that of the fine aggregates will help to mitigate the reduction in strength. Addition of steel and polypropylene fibres aids in maintaining the strength characteristics of rubcrete and facilitates control in the generation and propagation of cracks. Improved energy absorption characteristics were observed for steel and polypropylene fibre contents up to 1% and 0.3%, respectively. In order to determine the optimum proportions of crumb rubber, steel fibres and polypropylene fibres, the energy absorption capacity of prisms of size 100 × 100 × 500 mm was evaluated. Results show that 15% of crumb rubber, 0.75% of steel fibres and 0.2% of polypropylene fibres were the ideal proportions of crumb rubber, steel fibres and polypropylene fibres, respectively, to attain maximum energy absorption/cost ratio. This paper presents the results of numerical and experimental studies conducted on the impact behaviour of M 40 and M 60 grade ordinary concretes, rubcrete and fibre-reinforced rubcrete beams of dimensions 100 × 150 × 1200 mm. Durability studies were also carried out on fibre-reinforced rubcrete mixes to ascertain their behaviour in extreme environments. From the durability studies, it was noticed that when exposed to severe environments, fibre-reinforced rubcrete specimen had comparable properties with that of ordinary concrete.

Keywords Rubcrete · Steel fibre-reinforced rubcrete · Polypropylene fibre-reinforced rubcrete · Impact load

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Introduction

Structures are subjected to impact loads when any collision occurs in their vicinity [1, 2]. Pedersen et al. and Blok et al. had discussed impact loads caused due to the collision of ships on offshore structures [3, 4]. Some structures like crash barriers are subjected to impact forces due to collision from vehicles [5]. Blasts from various sources have different effects on structural elements. As such, sources of impact could vary from vehicular impact or any form of blast loads. Technological advancements have ensured more powerful automobiles and vessels occupy our roads and waterways to ferry greater loads in a single trip [6, 7]. Momentary lapses in concentrations of operators, excess speed, adverse weather, etc., during transport of these transport machines can lead to accidents, at least some of which result in damage to nearby by structural elements [8–11]. The blast loads may be generated by accidents or are purposely implanted. Blast accidents may occur in chemical plants, oil refineries, gas chambers, etc. Purposely planted blasts include blasts from bomb blasts implanted by security forces or antisocial elements and blasts generated for controlled demolition of buildings. The intensity of explosives has been on the rise. The effects of blast loads on structures were discussed by Ngo et al. [12]. The smaller projectiles generated during blasts create the impact loads during the blasts. Hence, it is essential to improve the energy absorption capacity of the structures, which are more likely to be subjected to blasts of impact loads. Since concrete is the most favoured material in terms of consumption across the globe, many of the structures erected are composed of concrete structural elements [13]. The concrete structures which are likely to be subjected to collision or blast would require concrete to absorb a significant amount of energy before failure.

So, attempts to improve the energy absorption capacity of concrete have been undertaken by various researchers. One of the methods to improve the energy absorption capacity of concrete is by replacing aggregates with rubber. When powdered or shredded rubber is used in the place of mineral aggregates, both fine and coarse, the material developed has the ability to absorb more energy. Such a concrete in which powdered or shredded rubber takes the place of mineral aggregates is generally termed as rubcrete [14, 15]. Ozbay et al. [16] had reported an increase in energy absorption capacity with an increase in replacement of fine aggregates with crumb rubber. Atahan and Yücel [17] had also reported an increase in energy absorption capacity of concrete with an increase in crumb rubber content. But, both Ozbay and Atahan had also reported a decrease in strength properties of concrete with an increase in crumb rubber content. One of the methods to reduce the decrease in strength properties of concrete is by pretreating the crumb rubber particles. The pretreatment of crumb rubber particles removes the unwanted materials from their surface and improves the adhesion of crumb rubber with other ingredients of the concrete matrix. Ganesan et al. and Wang et al. [18, 19] had reported an improvement in the strength characteristics of rubcrete due to the pretreatment of crumb rubber particles using polyvinyl alcohol.

Studies have also shown that adding fibres to rubcrete assists in mitigating the reduction in the strength properties of rubcrete. Carrol et al. [20] have reported an improvement in strength properties of steel fibre-reinforced rubcrete when compared to the strength properties of rubcrete. Steel fibres in concrete also regulate the propagation of macrocracks in concrete [21]. Raj et al. [22] have reported a significant improvement in the energy absorption capacity of steel fibre-reinforced rubcrete when compared to that of conventional concrete. Polypropylene fibres hold together various constituents of concrete and assist in delaying the generation of initial cracks. However, once the cracking has started, polypropylene fibres are rendered ineffective [23]. More importantly, there is evidence of improvement in the energy absorption capacity of polypropylene fibre-reinforced rubcrete when compared to the energy absorption capacity of conventional concrete [24].

Important structures have to withstand the loads acting on them effectively for a longer duration of time. Hence, assessment of the performance of concrete when subjected to an extreme environment is of paramount importance, to provide confidence to the user of the material about its enhanced performance and lower life cycle costs. Water absorption and sorptivity studies on specimen indicate the degree of permeability of concrete [25, 26]. Massazza [27] has presented sorption as a phenomenon induced due to the action of capillary forces acting on concrete surfaces which are subjected to repeated wetting and drying. Mackechnie had noted that the exposure of concrete to marine environment significantly affects the durability characteristics of concrete [28]. Marine environment adversely affects concrete and may abet the corrosion of reinforcements within concrete [29]. So, it is essential to understand the behaviour of concrete subjected to the marine environment. The resistance of concrete to the acidic environment and sulphate attack has not been effective [30, 31]. When the components of concrete that are soluble in acid get exposed to the acidic environment, they get degraded and increase the capillary porosity of concrete. The acid attack also results in loss of cohesiveness within the concrete and consequently results in a decrease in strength characteristics [32]. Exposure of concrete to sulphate attack causes the formation of products with larger molar volume and results in the cracking of concrete. Excessive deformation of concrete resulting in cracks is a sign of concrete subjected to sulphate attack [32]. So, in order to analyse the behaviour of constituents of concrete subjected to acidic and sulphate environment, it is essential to subject them to acid attack and sulphate attack.

It can be noted that the ability of concrete to withstand impact loads is limited. This limitation makes concrete structures that are likely to be subjected to impact or blast loads vulnerable. So, improving the impact resistance of concrete assumes significance. Addition of rubber as replacement of fine aggregates provides us with concrete having better energy absorption characteristics. But, reduced strength characteristics of rubber concrete hinder the widespread use of rubcrete. The reduction in the strength characteristics can be controlled by adding steel fibres and polypropylene fibres. The initial cracking in rubcrete can be controlled by adding polypropylene fibres. They assist in regulating the microcracks. The energy absorption capacity of polypropylene fibre-reinforced rubcrete is also higher than that of conventional concrete. Steel fibres, when added to concrete, can help in controlling the development and propagation of macrocracks in concrete. Apart from controlling the macrocracks, the steel fibre-reinforced rubcrete possesses significantly larger energy absorption capacity when compared to the conventional concrete. Thus, the use of fibre-reinforced rubcrete in structures subjected to impact loads helps to improve the energy absorption capacity of those structures. But, before implementing the material in actual structures, a considerable amount of studies have to be carried out to verify the utility of the material in such structures. But, only limited studies have been carried out in this direction. Hence, the present study focuses on the impact resistance of rubcrete, steel and polypropylene fibre-reinforced rubcrete beams. The fine aggregates in the concrete matrix were replaced with crumb rubber in the range of 0–20% by volume. Grading of crumb rubber was undertaken such that the particle size distribution curve of fine aggregate rubber matrix was similar to that of fine aggregates. Graded crumb rubber particles were pretreated with a polyvinyl alcohol solution. Steel and polypropylene fibre contents were varied in the ranges of 0.25–1% and 0.1–0.3%, respectively. The optimum proportion of replacement of fine aggregates with crumb rubber, steel fibre content and polypropylene fibre content was found out by conducting a drop-weight impact test on rubcrete prisms of dimension 100 mm × 100 mm × 500 mm. For maximum energy absorption, the optimum content of rubber was 15%, and those of steel and polypropylene fibres were found to be 0.75% and 0.2%, respectively. In many structures which are subjected to impact loads such as crash barriers, railway sleepers, etc., M 40 and M 60 grade concretes have been used as per the standards (RDSO-T-39-85 for railway sleepers, IRC-6 for crash barriers) [33, 34]. M 40 and M 60 grade concretes are generally brittle when compared to concrete grades up to M 30. Improvement in ductility of concrete is one of the main advantages obtained by using rubcrete. Addition of steel fibres and polypropylene fibres in M 40 and M 60 grade rubcretes further improves the ductility of concrete. Hence, in this study, M 40 and M 60 grade concretes were studied. The energy absorption capacity of M 40 and M 60 grade reinforced concrete beams was determined by conducting a drop-weight test on beams of dimension 100 mm × 150 mm × 1200 mm. Rubcrete beams (crumb rubber 15%), steel fibre-reinforced rubcrete beams (steel fibre 0.75% and crumb rubber 15%) and polypropylene fibre-reinforced rubcrete beams (polypropylene fibre 0.2% and crumb rubber 15%) were cast and tested. Numerical investigations were also carried out to assess the behaviour of rubcrete and fibre-reinforced rubcrete beams subjected to impact loads. Results of experimental and numerical investigations were compared, and benefit-to-cost ratio of beams was calculated. This paper also highlights the results of durability studies, viz. water absorption, sorptivity, marine water attack, acid attack and sulphate attack, carried out on M 40, and M 60 grade concrete, rubcrete and fibre-reinforced rubcrete specimens.

Investigations on Beams Subjected to Impact Loads

This section deals with the materials and methods, experimental and numerical studies on the energy absorption characteristics of concrete, rubcrete and fibre-reinforced rubcrete prisms of dimension 100 × 100 × 500 mm and reinforced concrete, rubcrete and fibre-reinforced rubcrete beams of dimension 100 × 150 × 1200 mm.

Materials and Methods

Ordinary portland cement of 53 grade was used for the study. Ding et al. had reported that using metakaolin to concrete improves the strength characteristics of concrete. Using metakaolin in concrete also reduces the shrinkage cracks in concrete. Hence, metakaolin was used as additional cementitious material for M 60 grade concrete. Locally available manufactured sand and 12 mm crushed stones were used as aggregates. Powdered crumb rubber of specific gravity 0.65 was procured from tyre retreading centres. Manufactured sand used for casting concrete conformed to Zone II of IS-383: 2016 [35]. Special care was taken to grade the rubber particles in such a manner that the rubber and aggregate mix also conformed to Zone II of IS-383:2016. Polycarboxylic ether-based high-range water reducer and sulphonated naphthalene polymer-based superplasticizer were used to attain workable combinations of M 60 and M 40 grade concrete, respectively. Crimped steel and polypropylene fibres of aspect ratios 60 and 600 were used in the study. Crumb rubber particles were pretreated by immersing them in 2% polyvinyl alcohol solution and mixed in 20% of the total water used for mixing the concrete for half an hour. Water-to-binder ratios used were 0.4 and 0.33 for M 40 and M 60 grade concrete, respectively. Extensive trials were carried out to arrive at suitable mix proportions for M 40 and M 60 grade concrete. While adding fibres, care was taken to ensure uniform mixing. Table 1 shows the mix designations and constituent proportions used in the paper. Tables 2 and 3 show the mix proportions of the mixes. The workability of mixes is presented in Fig. 1 [36, 37].

Compressive strength of rubcrete was determined based on IS 516-1959 (reaffirmed in 2004) [38]. Figure 2 presents the results of the compressive strength of rubcrete. It can be noticed that for the rubcrete mix with 20% replacement of fine aggregates with crumb rubber, the decrease in compressive strength was more than 30%. Hence, further works

Table 1 Proportions of the constituents

Mix ID	Grade of concrete	Rubber content (%)	Steel fibre content (%)	Polypropylene fibre content (%)
M60R1	60	0	0	0
M60R2	60	5	0	0
M60R3	60	10	0	0
M60R4	60	15	0	0
M60R5	60	20	0	0
M60R1SF1	60	0	0.25	0
M60R1SF2	60	0	0.5	0
M60R1SF3	60	0	0.75	0
M60R1SF4	60	0	1	0
M60R4SF3	60	15	0.75	0
M60R1PP1	60	0	0	0.1
M60R1PP2	60	0	0	0.2
M60R1PP3	60	0	0	0.3
M60R4PP2	60	15	0	0.2
M40R1	40	0	0	0
M40R2	40	5	0	0
M40R3	40	10	0	0
M40R4	40	15	0	0
M40R5	40	20	0	0
M40R1SF1	40	0	0.25	0
M40R1SF2	40	0	0.5	0
M40R1SF3	40	0	0.75	0
M40R1SF4	40	0	1	0
M40R1PP1	40	0	0	0.1
M40R1PP2	40	0	0	0.2
M40R1PP3	40	0	0	0.3
M40R4SF3	40	15	0.75	0
M40R4PP2	40	15	0	0.2

R stands for rubber. The number that follows *R* denotes the notation for the percentage of replacement of fine aggregates. SF and PP indicate steel fibres and polypropylene fibres, respectively. The number that succeeds SF and PP represents the percentage of fibres used in the study

on rubcrete mixes were limited to 15% replacement of crumb rubber.

Optimum Proportions of Rubber, Steel Fibre and Polypropylene Fibre

The process for determination of energy absorption capacity of concrete by conducting a drop-weight impact test on a concrete cylinder, the bottom surface of which is fully supported, is governed by ACI-544 [39]. But, for obtaining reliable results using fully supported cylinders, a very large sample size has to be tested [40]. Mamun and Bindiganavile, Zang et al. and Raj et al. [36, 37, 41, 42] have conducted drop-weight tests on simply supported beams and prisms to determine the energy absorption capacity of concrete. Hence, to obtain comparative results for establishing optimum proportions, energy absorption capacities of concrete, rubcrete, and fibre-reinforced rubcrete mixes were determined using simply supported prisms of dimension 100 × 100 × 500 mm [36, 37]. The energy absorption capacity of prisms was calculated by subjecting them to multiple impacts until failure by a 3.5 kg impactor from a height of 100 mm. Three specimens per mix were tested. The energy absorption capacity of prisms at the time of failure was determined by using Eq. 1. Figure 3 shows the schematic diagram of a drop-weight impact test on prisms.

$$U = Nmgh \tag{1}$$

where N stands for the number blows taken for the development of cracks on the prism. m in kg represents the mass of the impactor, h denotes the height of fall of the impactor in m and g stands for the acceleration due to gravity.

The results of the impact tests on the prisms are given in Figs. 4, 5 and 6 [36, 37]. Rubcrete specimen showed an increase in energy absorption capacity with an increase in crumb rubber content. The maximum energy absorbed/cost ratio was obtained for rubcrete specimen with 15% crumb rubber. Increase in the quantity of fibres improves the energy absorption capability of concrete. Maximum energy

Table 2 Mix proportions for M 40 grade mixes in (kg/m^3)

Mix ID	Cement	FA	CA	Water	Steel fibres	Polypropylene fibres	Superplasticizer	Rubber
M40R1	448	832.46	995.44	179.2	0	0	2.9	0
M40R4	448	723.85	995.44	179.2	0	0	2.9	31.1
M40R1SF3	444.64	826.21	987.98	177.86	58.88	0	2.9	0
M40R4SF3	444.64	718.42	987.98	177.86	58.88	0	2.9	30.86
M40R1PP2	447.10	830.79	993.45	178.84	0	1.82	2.9	0
M40R4PP2	447.10	722.41	993.45	178.84	0	1.82	2.9	31.04

FA fine aggregates, *CA* coarse aggregates

Table 3 Mix proportions for M 60 grade mixes (kg/m^3)

Mix ID	Cement	FA	CA	Water	Steel fibres	Polypropylene fibres	HRWR	VMA	Metakaolin	Rubber
M60R1	438	670	1192.01	161.7	0	0	4.4	1.8	40.6	0
M60R4	438	569.47	1192.01	161.7	0	0	4.4	1.8	40.6	24.46
M60R1SF3	437.69	664.94	1183.07	160.49	58.88	0	4.4	1.8	40.27	0
M60R4SF3	437.69	565.195	1183.07	160.49	58.88	0	4.4	1.8	40.27	24.28
M60R1PP2	440.19	668.62	1189.63	161.377	0	1.82	4.4	1.8	40.49	0
M60R4PP2	440.19	568.33	1189.63	161.377	0	1.82	4.4	1.8	40.49	24.42

FA fine aggregates, *CA* coarse aggregates, *HRWR* high-range water reducer, *VMA* viscosity-modifying agent

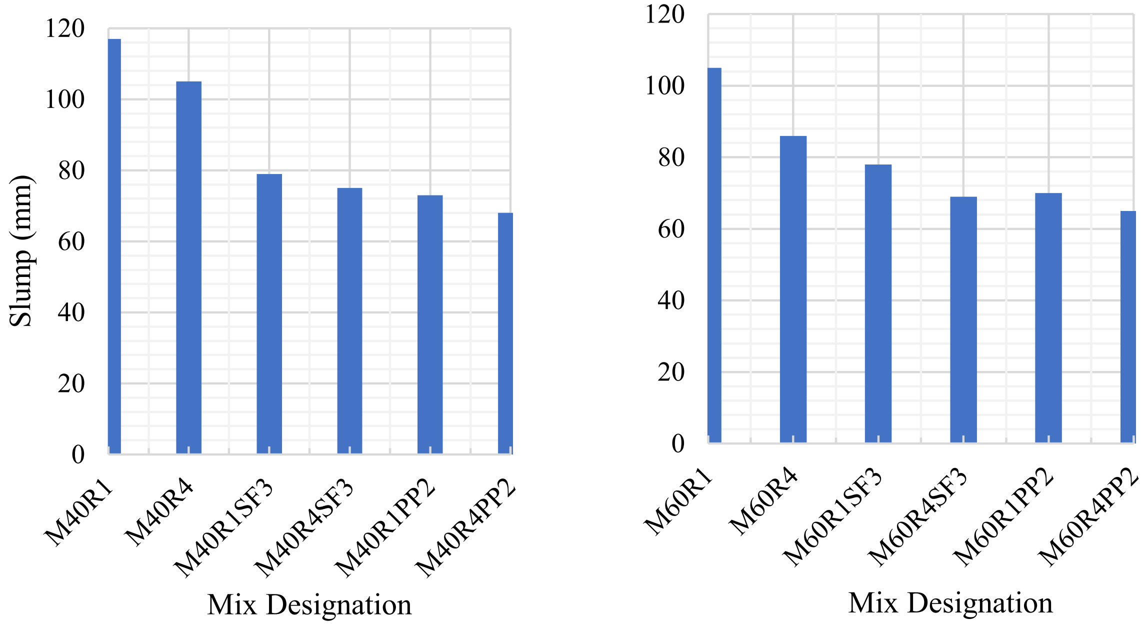


Fig. 1 Workability of mixes

absorbed/cost ratio for steel fibre-reinforced concrete specimen was observed for the steel fibre content of 0.75%. In the case of polypropylene fibre-reinforced concrete specimen, 0.2% polypropylene fibre content provided the maximum energy absorption capacity/cost ratio. So, further studies in concrete were carried out with crumb rubber replacing 15% volume of fine aggregate, steel fibre content of 0.75% and polypropylene fibre content of 0.2%.

Material Properties

Compressive strength of concrete cubes of 150 mm diameter was determined as per IS 516-1959 (reaffirmed in 2004) in a compression testing machine of capacity 3000 kN. Flexure strength of concrete prisms of dimension 100 × 100 × 500 mm was determined based on IS 516-1959 (reaffirmed in 2004) using a universal testing machine of capacity 400 kN. Tension tests on rebars were carried out in a universal testing machine of capacity 400 kN. Cylinders of 150 mm diameter and 300 mm height were used to assess the modulus of elasticity of mixes. The experiment for the determination of modulus of elasticity was done on a displacement-controlled universal testing machine of capacity 1000 kN. A displacement-controlled universal testing machine of capacity 10 kN was used to determine the fracture energy of 100 × 60 × 500 mm prisms with a central notch of 30 mm based on Rilem TC-50 FMC [43] as presented in [22, 44]. Figure 7 presents the load versus deflection plots of fracture energy studies.

Table 4 and Figs. 8 and 9 provide the details of the material properties of the mixes. When compared to the flexure strength of M 40 and M 60 grade concrete prisms, the flexure strength of M 40 and M 60 grade rubcrete prisms was lower by 14%. Flexure strength of M 40 grade polypropylene fibre-reinforced rubcrete prism was 9% lower than that of ordinary M 40 grade concrete prism. For

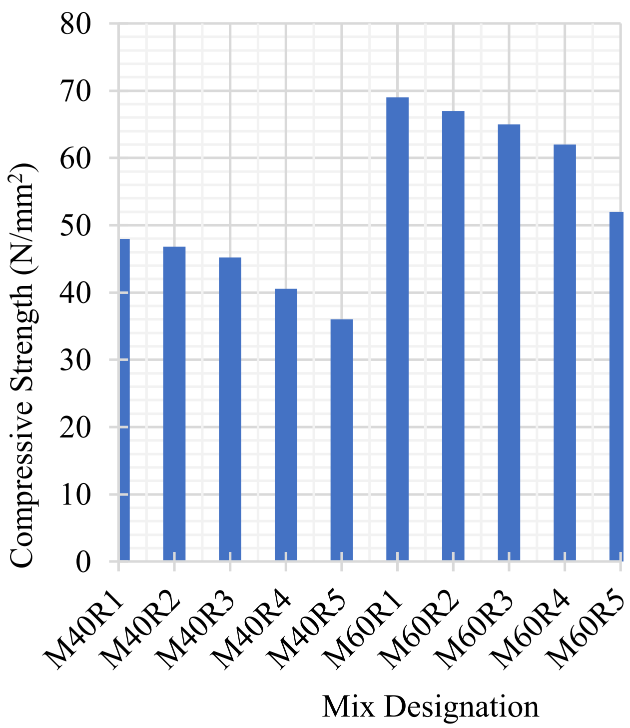


Fig. 2 Compressive strength of rubcrete mixes

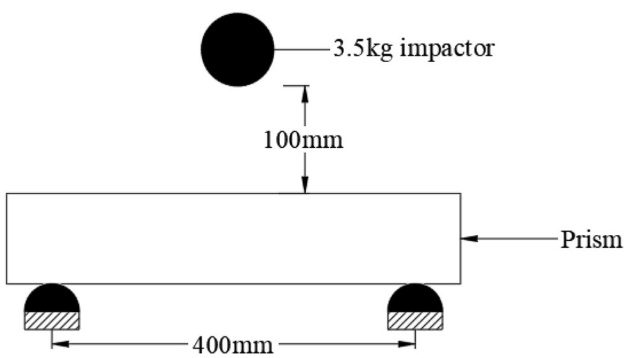


Fig. 3 Schematic diagram of the impact test on prisms

M 60 grade polypropylene fibre-reinforced rubcrete prisms, 5% reduction in the flexure strength was noticed in comparison with the flexure strength of M 60 grade concrete prisms. M 40 and M 60 grade steel fibre-reinforced rubcrete prisms had 2% and 5% more flexure strength when compared to the flexure strength of ordinary concrete prisms of M 40 and M 60 grade. In the case of rubcrete cylinders, the stress–strain curves had lower peaks than the ordinary concrete cylinders. Increase in strain corresponding to peak stress was observed for the stress–strain curve of rubcrete cylinders when compared to that of ordinary concrete cylinders. Ultimate strains of fibre-reinforced rubcrete cylinders had increased in comparison with the ultimate strains of ordinary concrete cylinders.

Impact Test on Beams

This section deals with the experimental studies on the impact behaviour of a typical under-reinforced beam of dimension 100 mm × 150 mm × 1200 mm. Figures 10 and 11 show the cross section of the beam used for the study and the schematic diagram for the impact testing of beams. Table 5 provides the details of the beams cast.

Drop-weight impact test set-up was fabricated to carry out the experimental investigations on beams. An electrically controlled motor was used to control the height of the drop of the impactor. The motor has the capacity to lift weights ranging from 3 to 50 kg. Drop height could be varied from 0 to 1200 mm. Figure 12 presents the testing arrangement for the drop test on beams. Multiple drops were carried out until the development of cracks at the bottom of the beams to mark the failure.

Numerical Investigations on Impact Tests on Beams

Numerical studies on the impact characteristics of beams were carried out using finite element software ANSYS. Three-dimensional modelling was done in the ANSYS workbench design module. Since the application of load on the structure exists for only a short duration, explicit dynamics solver was utilized for the analysis. For conducting impact testing of concrete elements, usually, the RHT model has been used. But the defect in the in-built RHT model in ANSYS workbench is that the default parameters are available only for 35 MPa and 140 MPa concrete. So, in this paper, numerical studies were carried out using a combination of multilinear isotropic hardening behaviour of concrete and crack softening model in ANSYS workbench. Engineering data for the analysis were derived from the conduct of experiments. Tables 6, 7 and 8 and Figs. 8, 9 and 13 ("Material Properties" section) present the data used to create the material models. Modelling of geometry was carried out in the geometry module of ANSYS workbench design modeller. The cross section of the beam was modelled and extruded to develop the beam geometry. Separate section planes were used to model the longitudinal and transverse reinforcement. Figures 14 and 15 deal with the modelling of the beam.

The concrete, steel reinforcement and impactor models were modelled in the geometric modeller, and the properties were assigned to them. The impactor was provided with the in-built structural steel material property available in ANSYS workbench. The contact between the concrete

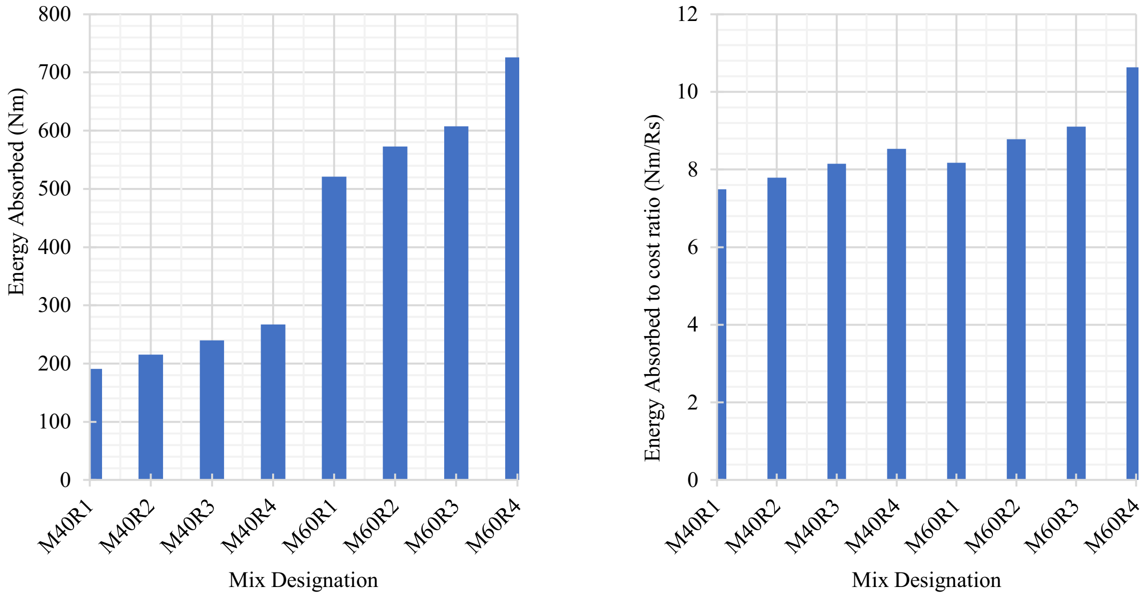


Fig. 4 Energy absorption characteristics of rubcrete prisms

surface and the impactor was taken as frictionless. The connection between the rebars and the surrounding concrete was provided as fully bonded. The base of the supports was fixed and was provided with zero displacements in all directions. Mesh size of 15 mm was used based on the mesh sensitivity analysis. Hexahedral meshing of the model was undertaken, resulting in the generation of 11903 nodes and 9087 elements after meshing. Principal stress failure criterion was adopted for the failure of the materials. The velocity of the impactor was varied at an increment of 100 mm/s until the appearance of cracks at the bottom of the beam. Figure 16 presents the meshed model. Figure 17 shows the direction of velocity on the impactor. The energy absorbed by the beams was found out using Eq. 2.

$$U = 0.5 \times m \times v^2 \tag{2}$$

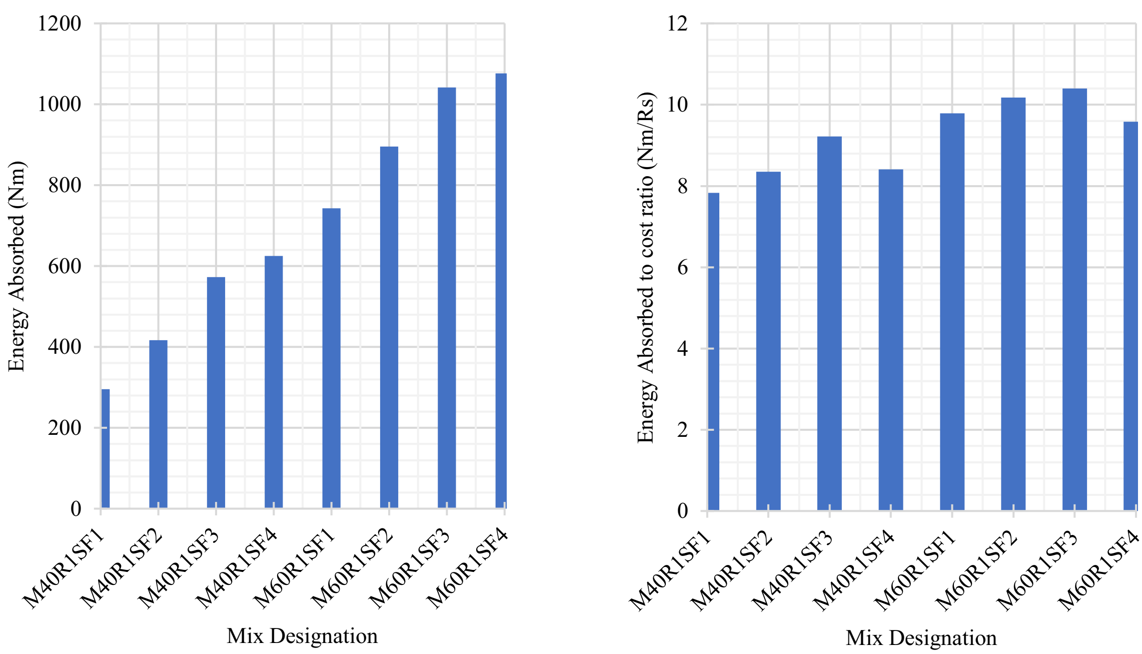


Fig. 5 Energy absorption characteristics of steel fibre-reinforced concrete prisms

Table 4 Material properties

Mix ID	Compressive strength (N/mm^2) [36, 37]	Flexure strength (N/mm^2) [36, 37]	Modulus of elasticity (N/mm^2)	Fracture energy (Nm/m^2) [22, 44]
M40R1	48	4.4	25,300	127
M40R4	41	3.8	11,250	143
M40R4PP2	43	4	14,200	172
M40R4SF3	47	4.6	25,700	222
M60R1	69	5.8	33,000	175
M60R4	62	5	32,700	198
M60R4PP2	63	5.5	31,500	225
M60R4SF3	68	5.9	32,400	278

Table 5 Details of beams cast

Specimen ID	Number of beams cast
M40R1	3
M40R4	3
M40R4PP2	3
M40R4SF3	3
M60R1	3
M60R4	3
M60R4PP2	3
M60R4SF3	3

where U is the energy absorbed in Nm, m is the mass of the impactor in kg and v is the velocity in m/s.

Durability Studies on M 40 and M 60 Grade Concrete

Important public buildings have to be of service for at least five decades. So, the material that is used in such structures should be durable. Significance of durability studies lies in understanding the behaviour of concrete when it is exposed to severe conditions. Deterioration of severely exposed concrete renders the steel reinforcement vulnerable to corrosion and subsequent deterioration of the structure. In this paper, results of water absorption and sorptivity of concrete and 90-day durability of concrete exposed to marine water attack, acid attack and sulphate attack are presented. The details of the specimens cast for durability tests are shown in Table 9.

Water Absorption

Penetration of water into concrete is a critical durability factor that relates to the amount of pores in it. In real structures, it is crucial because more water absorption means more contact of embedded reinforcement with water. Water absorption was determined as per IS 1124-1974 (reaffirmed 2003) [45]. After 28 days of curing, 100 mm cubes were wiped dry and placed in an oven for drying. After 24 h, the weight of the oven-dried sample was taken. Then, the specimens were immersed in water for 24 h. The wet weight of the specimen was taken after wiping the moisture from the surface. The percentage of water absorbed is presented as Eq. 3:

$$\text{Percentage of water absorbed} = \frac{(w_2 - w_1) \times 100}{w_1} \tag{3}$$

Sorptivity Test

Intrusion or ingress of water through the pores in the vicinity of the surface of the concrete is critical in abetting the corrosion of steel in concrete. Sorptivity provides a measure of this infiltration of water through the pores. The degree of moisture content in the pores of concrete varies from a minimum at the exposed surface of a relative maximum near to the core of the structure. During hot seasons, the moisture content at the surface of the concrete will be approximately zero. Rainy season brings saturation of moisture at the surface concrete. Variation in seasons thus brings about varying saturation levels of moisture content from the surface to the interior of concrete. Capillary suction forces act in empty cavities in concrete and assist the movement of water into it. The intruding water may have the presence of harmful ions which may accelerate the process of corrosion of embedded steel reinforcement. Hence, it is necessary to assess the quality of surface concrete in terms of its sorptivity [46]. In this paper, the sorptivity of specimens was determined by the method prescribed by ASTM C1585-04 [47].

The peripheral surface of the cured and oven-dried cylinders were wrapped with a non-absorbent filament. The cylinders were then immersed in water in such a way the depth of specimen underwater was at most 5 mm. At the end of 30 min, the weight of the specimen was measured within 30 s of lifting the specimen from water. Figures 18 and 19 show the wrapping of nonabsorbent filament over the concrete cylinders and sorptivity testing of cylinders, respectively. Equation 4 presents the formula to find out the sorptivity:

$$S = \frac{I}{t^{\frac{1}{2}}}$$

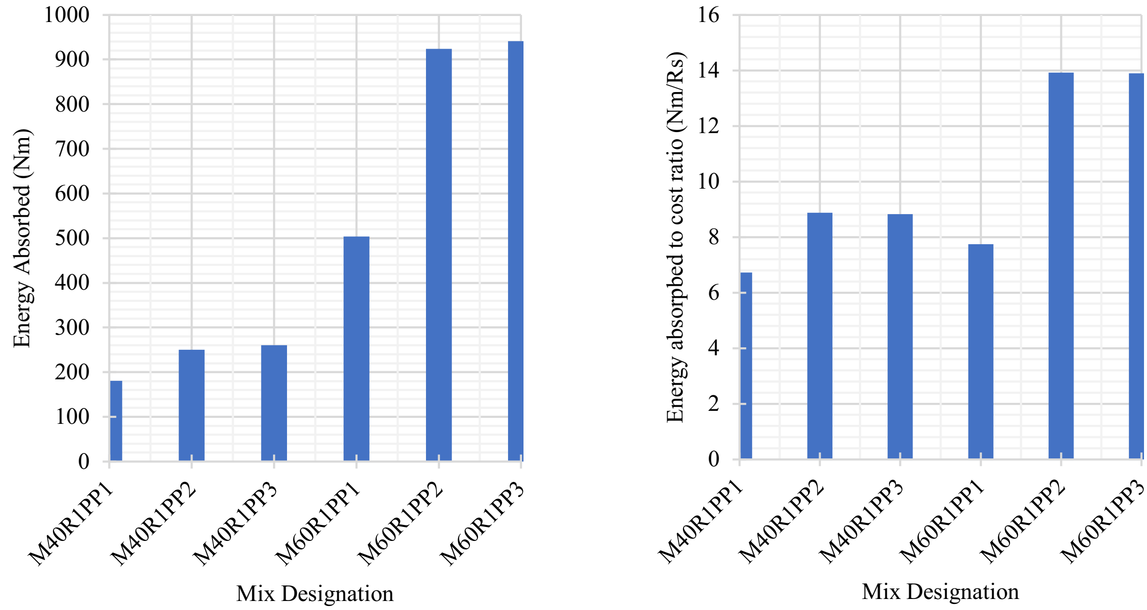


Fig. 6 Energy absorption characteristics of polypropylene fibre-reinforced concrete prisms

$$I = \frac{\Delta W}{Ad} \quad (4)$$

where S is sorptivity in mm and t is the elapsed time in minutes. ΔW is the change in weight of cylinders. A is the surface area of the specimen through which water penetrates. d is the density of water.

Marine Water Test

Effect of contents of marine water on the different constituents of concrete is essential precisely because of the faster deterioration of concrete components under the marine environment. Composition of artificial marine water was prepared in the laboratory as per ASTM D 1141 [48]. Table 10 shows the chemicals used to prepare the

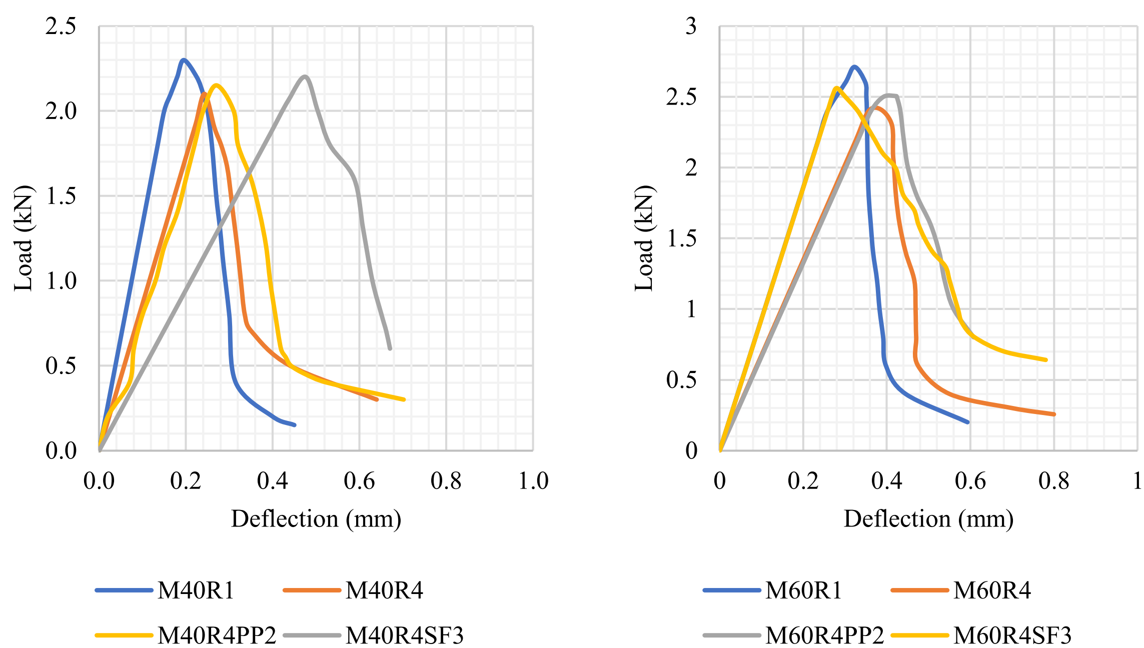


Fig. 7 Load versus deflection plots of fracture energy studies

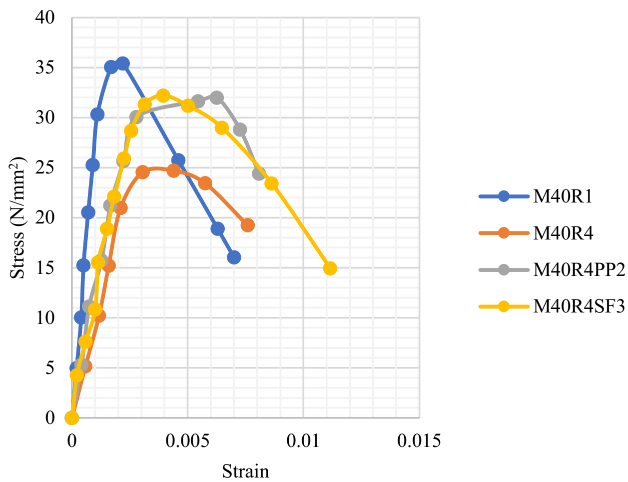


Fig. 8 Stress–strain curve of M 40 grade concrete

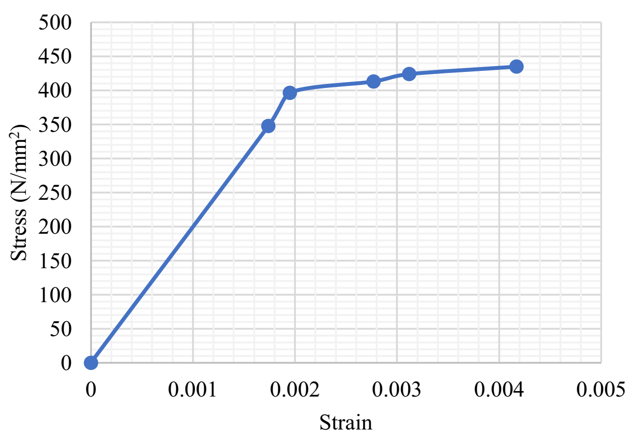


Fig. 9 Stress–strain curve of 8-mm-diameter reinforcement

marine water solution. Figure 20 shows the immersion of cubes in artificial marine water.

Acid Attack and Sulphate Attack Test

Susceptibility of concrete to attack by acids is high. Both the external surface and internal composition of concrete face a high risk of damage when exposed to acidic surroundings, and sulphate ions in sulphuric acid aid deterioration of concrete by assisting sulphate attack. Reduction in strength characteristics and density of concrete is noticed when concrete is exposed to a severe acidic environment. The bonding between constituents of concrete becomes weak due to chemical reactions when they come in contact with sulphate ions over a long period of time. As a result, spalling, cracking and degeneration of bonds in concrete occur, resulting in weak performance of concrete. Figures 21 and 22 show the immersion of cubes in acid and sulphate solution, respectively.

Hewayde et al. and Ghrici et al. had pointed out that 3% H_2SO_4 solution has to be used for the representation of the severe acidic environment [49]. The effect of acid attack on concrete, rubcrete and fibre-reinforced rubcrete of M 40 and M 60 grade concrete was studied by dipping the specimen in 3% H_2SO_4 solution for 90 days. For sulphate attack test, 30 g/l of Na_2SO_4 solution represents ten times the exposure conditions available in the laboratory and field as referred by Ikumi et al. and Chabrelie et al. [50, 51]; 100 mm cubes of M 40 and M 60 grade concrete, rubcrete and fibre-reinforced rubcrete were immersed in sodium sulphate solution of 30 g of Na_2So_4/lit for 90 days to assess the performance of concrete subjected to sulphate attack.

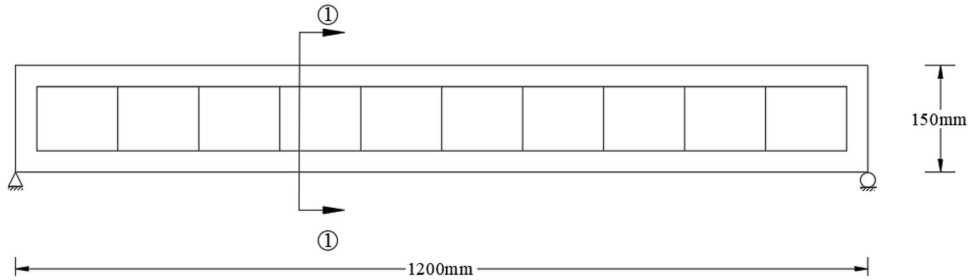
Results and Discussion

This section deals with the results and discussions on the experimental and numerical investigations carried out to ascertain the impact behaviour of reinforced concrete beams of M 40 and M 60 grade concrete, rubcrete and fibre-reinforced rubcrete. Results of durability studies on M 40 and M 60 grade concrete, rubcrete and fibre-reinforced rubcrete are also discussed in this section. Results and discussions are presented under the following three subsections.

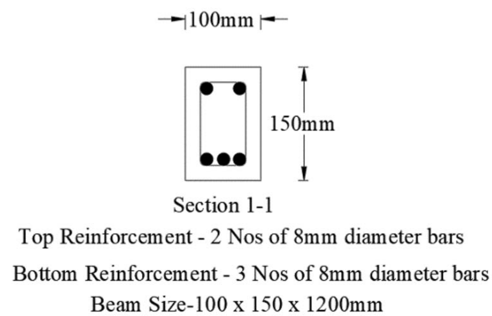
Investigations on Beams Subjected to Impact Loads

Figures 23, 24, 25 and 26 present the results of studies on the impact behaviour of beams. Rubber particles in rubcrete participate in the absorption of energy imparted due to the collision of the impactor much better than the other constituents of concrete. Hence, the energy absorbed by rubcrete specimens was enhanced by 6% and 12%, respectively, for M 40 and M 60 grade concrete with respect to the energy absorption of concrete beams. M 40 grade polypropylene fibre-reinforced rubcrete beam exhibited 81% improvement in energy absorption capacity when compared to the energy absorption capacity of concrete beams. Steel fibre-reinforced rubcrete beam of M 40 grade showed 175% improvement in its energy absorption capacity when compared to the energy absorption capacity of concrete beams. The energy absorption capacity of M 60 grade polypropylene fibre-reinforced rubcrete beams was 104% more than that of the reference M 60 grade beam. Steel fibre-reinforced rubcrete beam of M 60 grade showed an enhancement of 183% in its energy absorption capacity when compared to the concrete beam. Hence, it can be

Fig. 10 Details of the beam. **a** Geometry of the beam (all dimensions in mm). **b** Section 1-1

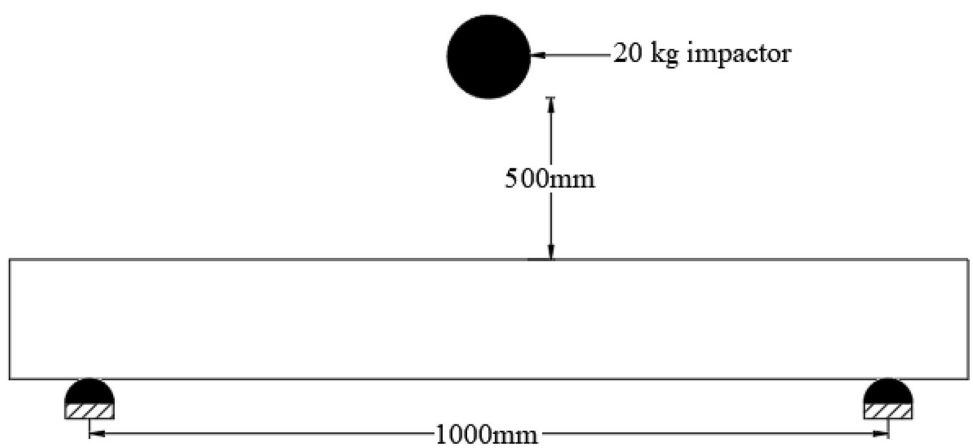


10.a) Geometry of the beam (All dimensions in mm)



10.b) Section 1-1

Fig. 11 Schematic diagram of impact test on beams



inferred that the use of steel fibre-reinforced rubcrete beams instead of concrete beams provides the optimum results with respect to the energy absorption characteristics. The rubber particles in rubcrete beams absorb and dissipate considerable energy in comparison with the other material constituents of concrete. Hence, the energy absorbed by rubcrete beams was noticed to be higher than that of the concrete beams. In the case of polypropylene fibre-reinforced rubcrete beams, the polypropylene fibres bridge the gaps present in the material matrix and assist in considerably delaying the initial cracks. But once the initial cracks widen, the role played by the polypropylene fibres is minimal. This action of polypropylene fibres and the natural energy absorption capability of crumb rubber particles act together in polypropylene fibre-reinforced rubcrete beams. Hence, the energy absorbed by polypropylene fibre-reinforced rubcrete beam is more than that of concrete and rubcrete beams. The energy that had to be spent to break the bonds established by rigid crimped steel fibres was considerably higher than the energy that had to be spent on breaking the bonds created by polypropylene fibres. Coupled with the natural absorption capacity of rubber particles, the combined action of steel fibres and crumb rubber was responsible for the significantly higher energy

Fig. 12 Drop-weight test on beams

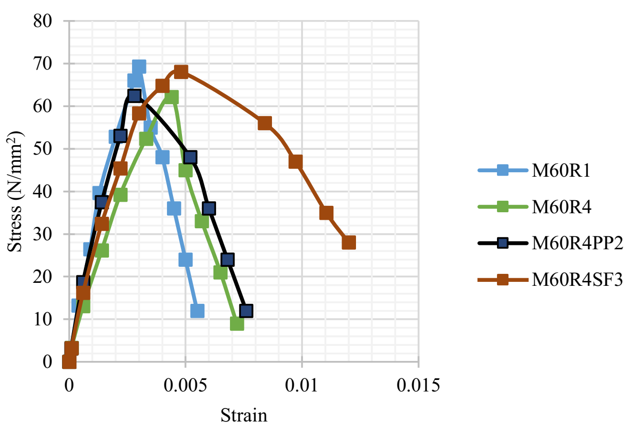


Fig. 13 Stress–strain curve of M 60 grade concrete

absorption capacity of steel fibre-reinforced rubcrete beams. The fracture energy of rubcrete and fibre-reinforced rubcrete specimen presented by Raj et al. can be taken as indicators of improvement in the energy absorption capacity of rubcrete and fibre-reinforced rubcrete beams [22, 44]. Hence, steel fibre-reinforced rubcrete beams of M 40 and M 60 grade concrete can find application in structures that require higher energy absorption capacity like beams used in walls built near the walls, wheel stoppers in parking lots and even on locations where the beams can be found vulnerable to pounding. While carrying out numerical investigations, the velocity of the impactor was varied, starting from zero until the development of cracks at the bottom. Failure pattern showed a similar pattern to those observed in experimental studies. The energy absorbed by rubcrete beam and fibre-reinforced rubcrete beams showed

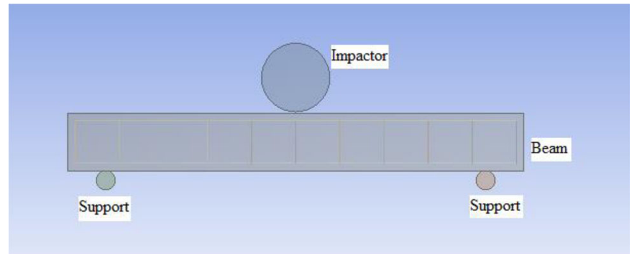


Fig. 14 Geometry of the beam in ANSYS Workbench design modeller

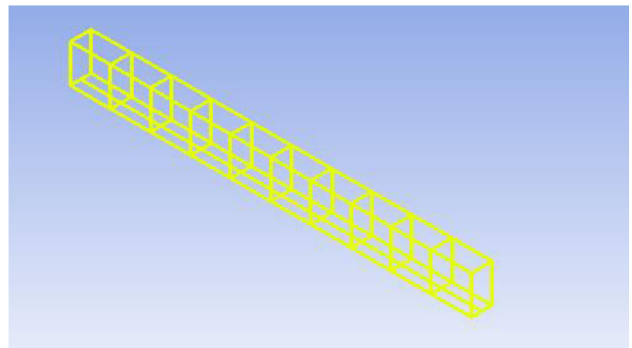


Fig. 15 Modelling of reinforcement of beams

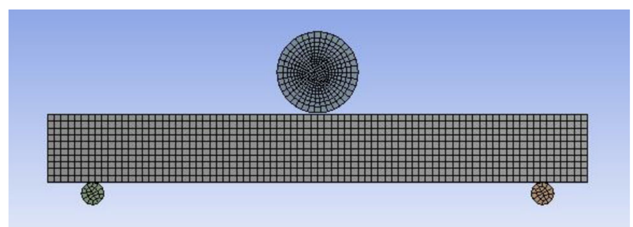


Fig. 16 Meshing of the beam model

similar trends to that obtained during experimental investigations.

Durability Studies

This section presents the results of water absorption tests, sorptivity tests, acid attack test, marine water test and sulphate attack tests on concrete, rubcrete and fibre-reinforced rubcrete specimens. Results of durability studies are presented under the following five subsections.

Compressive Strength of 100 mm Cubes

Twenty-eighth-day compressive strength of 100 mm cubes is presented in Fig. 27. Compressive strength of M 40 grade rubcrete cube was 18% lower than the compressive strength of M 40 grade ordinary concrete cube. M 40 grade polypropylene fibre-reinforced rubcrete cube had

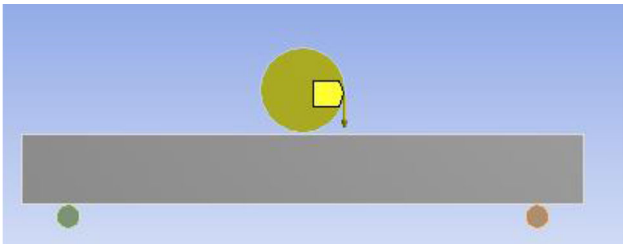


Fig. 17 Application of velocity on the impactor

Fig. 18 Specimen wrapped in nonabsorbent filament around concrete cylinders

Fig. 19 Sorptivity testing on cylinders

Fig. 20 Specimens immersed in artificial marine water

compressive strength which was 14% lower than the compressive strength of M 40 grade ordinary concrete cube. Steel fibre-reinforced rubcrete cube of M 40 grade concrete had 6% lower compressive strength in comparison with M 40 grade ordinary concrete cube.

For M 60 grade rubcrete cubes, the compressive strength was 15% lower than the compressive strength of M 60 grade concrete cube. Reduction in compressive strength of 11% was observed for polypropylene fibre-reinforced rubcrete cube of M 60 grade when compared to the compressive strength of M 60 grade concrete cubes. The compressive strength of steel fibre-reinforced rubcrete cube of M 60 grade was at par with the compressive strength of M 60 grade concrete cube.

Fig. 21 Specimens immersed in acid

Fig. 22 Specimens immersed in sulphate solution

Fig. 23 Cracking at the centre bottom of the beam (typical)

Fig. 24 Crushing at the top of the beam (typical)

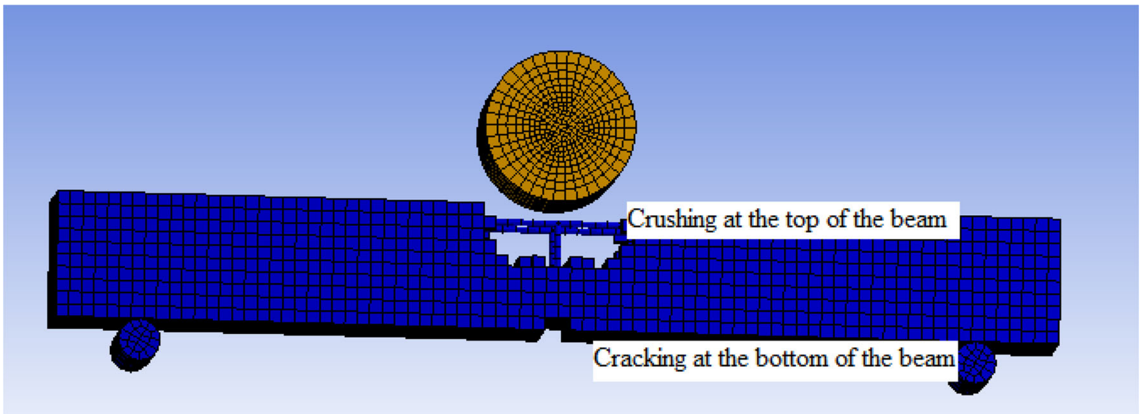


Fig. 25 Failure of impact studies of beams in numerical analysis (typical)

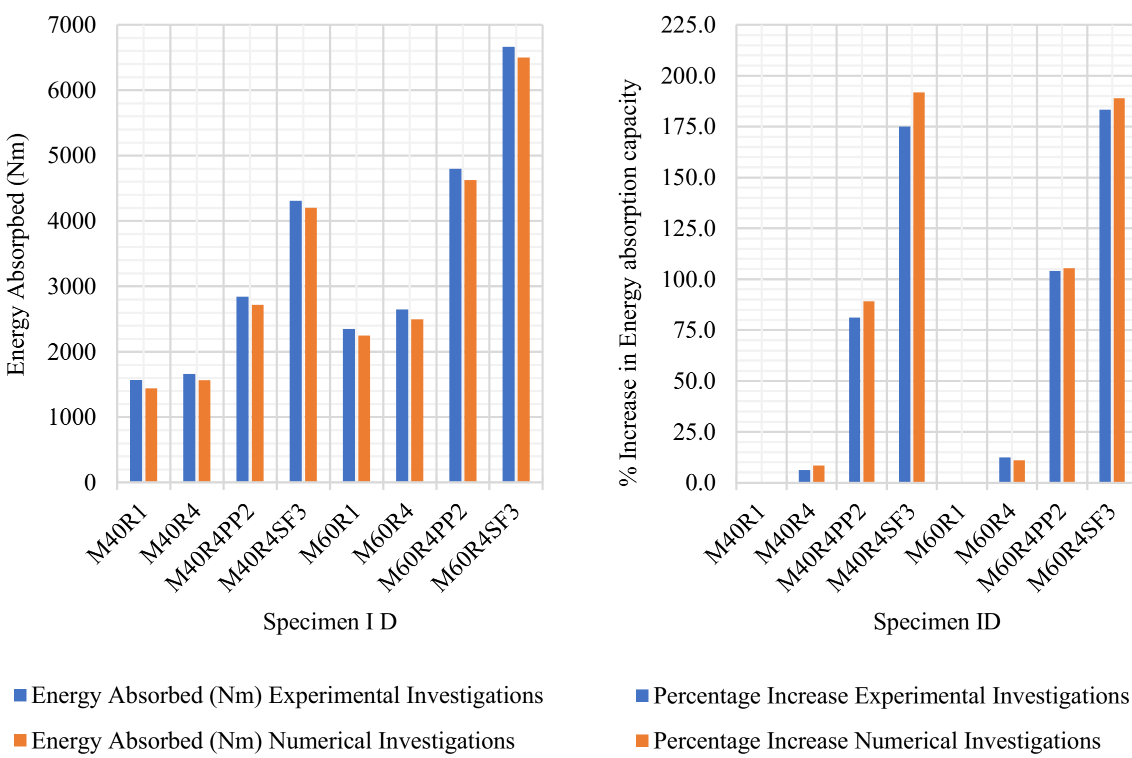


Fig. 26 Energy absorption characteristics of beams

Water Absorption and Sorptivity Tests

Percentage of water absorption of cubes of dimensions 100 mm is shown in Table 11. International Federation for Structural Concrete describes concrete with early water absorptions of less than 3% as good [52]. Table 12 shows the results of the sorptivity test. Sorptivity of the rubcrete specimen was increased by 0.82×10^{-2} mm/min$^{0.5}$ and 0.68×10^{-2} mm/min$^{0.5}$, respectively, for M 40 and M 60 grade rubcrete specimens. Increase in the sorptivity by

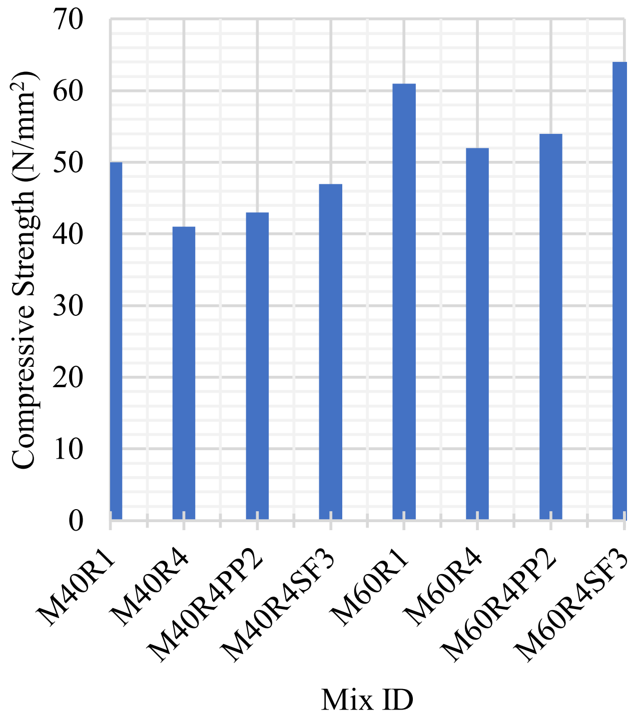


Fig. 27 Compressive strength of 100 mm cubes

0.62×10^{-2} mm/min$^{0.5}$ and 0.79×10^{-2} mm/min$^{0.5}$ was noticed for polypropylene fibre-reinforced rubcrete specimen, respectively, of M 40 and M 60 grade of concrete. Sorptivity of steel fibre-reinforced rubcrete specimen was greater by 1.63×10^{-2} mm/min$^{0.5}$ and 1.36×10^{-2} mm/min$^{0.5}$. The sorptivity values of all specimens were in the permissible range up to 9×10^{-2} mm/min$^{0.5}$. From the results of sorptivity tests, it can be inferred that, though the penetration of water into concrete increases with the addition of rubber and fibres, the performance of all the mixes, viz. concrete, rubcrete, steel fibre-reinforced rubcrete and polypropylene fibre-reinforced rubcrete, is within the permissible limit of 9×10^{-2} mm/min$^{0.5}$. So, for both M 40 and M 60 grade concrete, it can be safely noted that steel fibre-reinforced rubcrete, which had significant improvement in the energy absorption capacity, performs satisfactorily with respect to sorptivity and water absorption.

Marine Water Test

When the specimens were exposed to the marine environment for 90 days, it was observed that the weight and compressive strength of the cubes were reduced in comparison with those of the unexposed cubes. While the reduction in the weights of the exposed specimens was nominal, a considerable decrease in the compressive strengths of the exposed specimens was observed. Compressive strengths of M 40 and M 60 grade concrete specimen were lower by 20% and 15%, respectively. The decreases in the compressive strengths of M 40 and M 60 grade rubcrete specimen were 10% and 8%, respectively. After 90-day exposure to artificial marine water, the compressive strengths of M 40 and M 60 grade polypropylene fibre-reinforced rubcrete specimens were, respectively, decreased by 12% and 10%. Reduction in compressive strengths of steel fibre-reinforced rubcrete specimen of M 40 and M 60 grade was 15% and 10%,

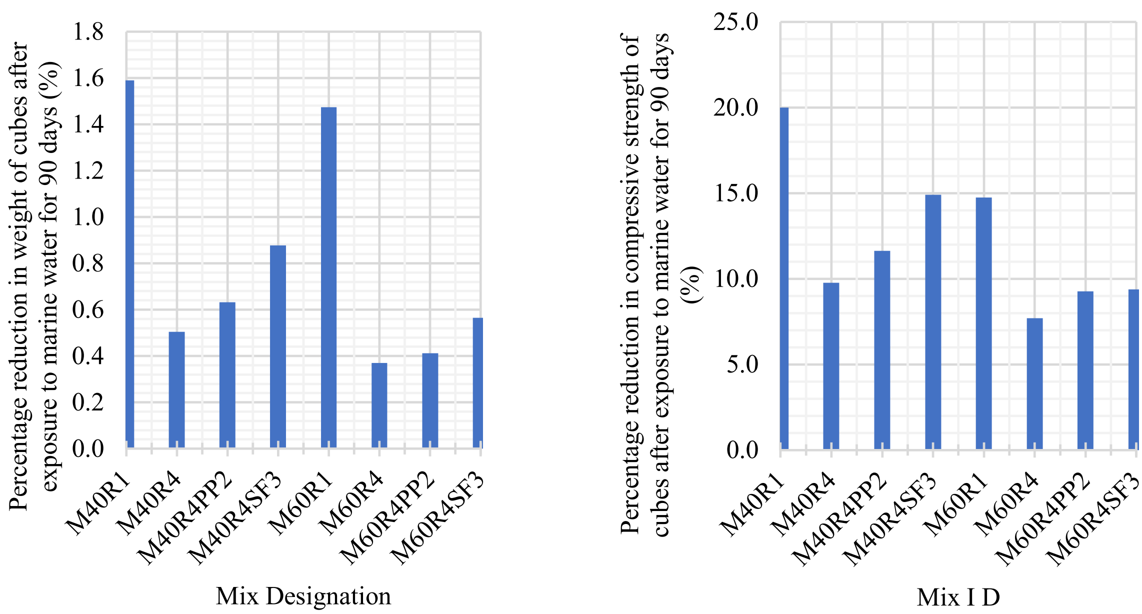


Fig. 28 Reduction in weight and compressive strength of cubes exposed to marine water for 90 days

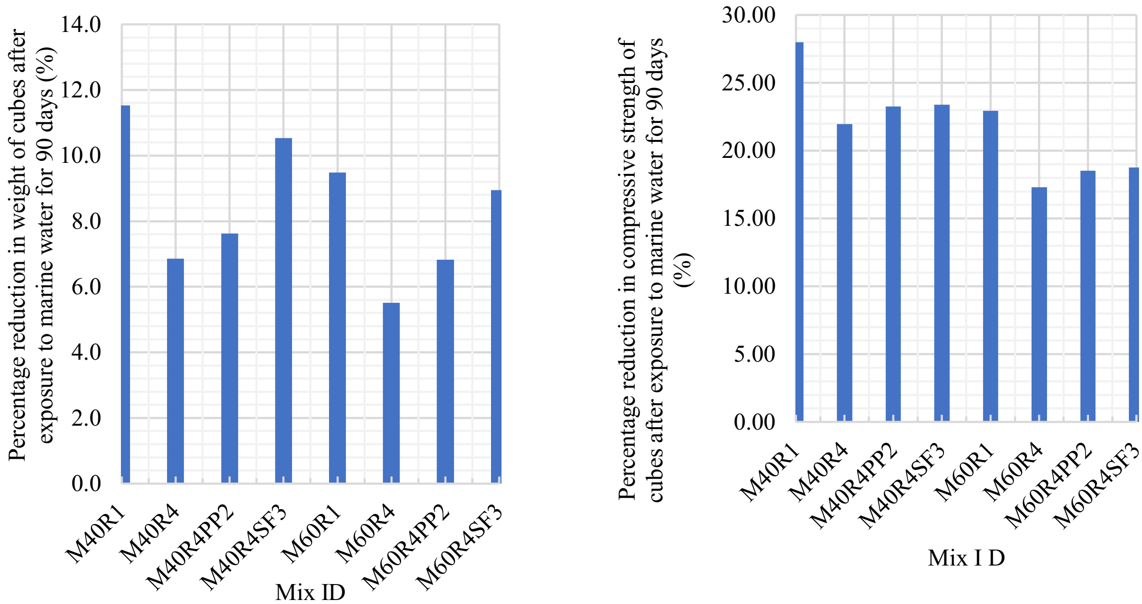


Fig. 29 Reduction in weight and compressive strength of cubes exposed to acidic environment for 90 days

Table 6 Material model for M 40 concrete

Material	M40R1	M40R4	M40R4PP2	M40R4SF3
Density (kg/m^3)	2322	2277	2275	2482
Isotropic elasticity (N/mm^2)	25,300	11,250	14,200	25,700
Poisson's ratio	0.18	0.18	0.18	0.18
Maximum tensile stress (N/mm^2)	4.4	3.8	4	4.6
Multilinear isotropic hardening	As in stress–strain curve			

Table 7 Material model for M 60 concrete

Material	M60R1	M60R4	M60R4PP2	M60R4SF3
Density (kg/m^3)	2696	2520	2500	2702
Isotropic elasticity (N/mm^2)	33,000	32,700	31,500	32,400
Poisson's ratio	0.18	0.18	0.18	0.18
Maximum tensile stress (N/mm^2)	5.8	5	5.5	5.9
Multilinear isotropic hardening	As in stress–strain curve			

Table 8 Material model for rebar and impactor

Material	Fe500	Impactor
Density (kg/m^3)	7850	7850
Isotropic elasticity (N/mm^2)	2.1×10^5	2.1×10^5
Poisson's ratio	0.3	0.3
Maximum tensile stress (N/mm^2)	545	–
Multilinear isotropic hardening	As in stress–strain curve	–

Fig. 30 Reduction in weight and compressive strength of cubes exposed to sulphate attack for 90 days

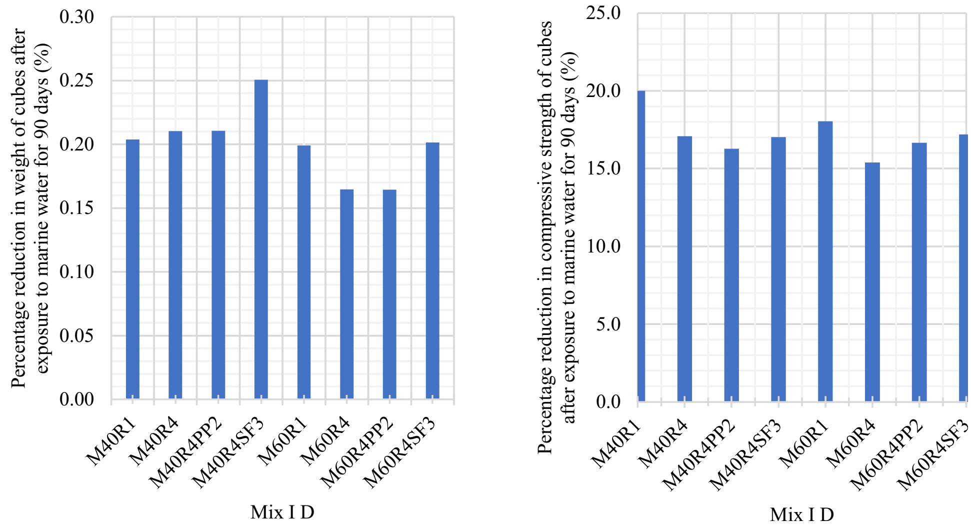


Table 9 Details of specimens cast for durability tests

Test	Specimen	Number of specimens
Water absorption	100 mm cubes	24
Marine water test	100 mm cubes	24
Acid resistance	100 mm cubes	24
Sorptivity	100-mm-diameter cylinder with height 50 mm	24
Sulphate attack	100 mm cubes	24

Table 10 Chemicals used to prepare the marine water solution

Composition	Concentration(g/lit)
Sodium chloride	24.53
Magnesium chloride	5.2
Sodium sulphate	4.09
Calcium chloride	1.16
Potassium chloride	0.695

respectively. Figure 28 shows the reduction in weight and compressive strength of cubes exposed to marine water for 90 days. The percentage reduction in weight and compressive strength of steel fibre-reinforced rubcrete cubes was lower than that of the concrete cubes. Thus, when the performance of steel fibre-reinforced rubcrete is analysed with respect to the susceptibility to degrade when marine water, it performs better than the concrete mix.

Table 11 Percentage of water absorption for specimens

Mix ID	% of water absorption
M40R1	0.76
M40R4	1.53
M40R4PP2	1.64
M40R4SF3	1.85
M60R1	0.67
M60R4	1.17
M60R4PP2	1.28
M60R4SF3	1.57

Acid Attack Test

There was a significant reduction in weight and compressive strength of the cubes subjected to the acidic environment for 90 days. The weights of concrete cubes were reduced by 12% and 10% for M 40 and M 60 grade concrete, respectively. Rubcrete specimens showed a reduction in weight of 7% and 6%, respectively, for M 40 and M 60 grade concrete. Exposure to 90 days of the acidic environment resulted in a decrease in weight of 8% and 7%, respectively, for polypropylene fibre-reinforced rubcrete specimens of M 40 and M 60 grade. When steel fibre-reinforced rubcrete specimens were subjected to acidic surroundings, 11% and 9% reduction in weights of cubes was observed for M 40 and M 60 grade cubes, respectively.

Compressive strengths of M 40 and M 60 grade concrete cubes were, respectively, reduced by 28% and 23% when they were exposed to an acidic environment. Reduction in compressive strengths for rubcrete cubes was by 22% and 18%, respectively, for M 40 and M 60 grade rubcrete cubes. When exposed to the acidic environment, the

Table 12 Sorptivity of specimens

Mix ID	Sorptivity value in 10^{-2} mm/min$^{0.5}$
M40R1	1.16
M40R4	1.98
M40R4PP2	1.78
M40R4SF3	2.79
M60R1	0.82
M60R4	1.50
M60R4PP2	1.61
M60R4SF3	2.18

Table 13 Unit cost for materials

Material	Cost/kg (Rs)
Cement	8.00
Metakaolin	95.56
Rubber	40.00
Sand	0.66
CA	0.63
Superplasticizer	115.00
High-range water reducer	250
VMA	350
Steel fibre	92.00
Polypropylene fibre	300.00
Steel reinforcement	60.00
Bar benders wage	800/day

Table 14 Energy absorption/cost ratio of beams

Specimen ID	Energy absorbed (Nm)	Cost per beam (Rs)	Energy absorbed/cost ratio (Nm/Rs)
M40R1	1568	1108	1.42
M40R4	1666	1129	1.48
M40R4PP2	2842	1139	2.50
M40R4SF3	4312	1226	3.52
M60R1	2352	1246	1.89
M60R4	2646	1262	2.10
M60R4PP2	4802	1302	3.69
M60R4SF3	6664	1393	4.78

compressive strengths of polypropylene fibre-reinforced rubcrete cubes were reduced by 24% and 19%, respectively, for M 40 and M 60 grade cubes. In the case of steel fibre-reinforced rubcrete cubes, 24% and 19% reductions in compressive strengths were observed for M 40 and M 60 grade concrete cubes, respectively. Figure 29 shows a decrease in weight and compressive strength of cubes exposed to an acidic environment for 90 days.

Sulphate Attack Test

Significant reduction in compressive strength was noticed for cubes subjected to sulphate attack for 90 days. Reduction in compressive strength of cubes was nominal when they were exposed to sulphate attack. Reduction in compressive strength of concrete cubes was 20%, and 18%, respectively, for M 40 and M 60 grade concrete. The decrease in compressive strength was 17% and 16% for M 40 and M 60 grade rubcrete cubes, respectively. For polypropylene fibre-reinforced rubcrete cubes subjected to sulphate attack for 90 days, the compressive strength was reduced by 17% for M 40 and M 60 grade cubes. When steel fibre-reinforced rubcrete cubes were exposed to sulphate attack for 90 days, 17% and 18% reductions in compressive strength were observed for M 40 and M 60 grade cubes, respectively. Figure 30 presents the decrease in weight and compressive strength of cubes exposed to sulphate attack for 90 days.

When crumb rubber replaces fine aggregates, additional voids or pores are induced in concrete [53]. These voids allow the ingress of water into concrete. Hence, the sorptivity and water absorption in rubcrete specimen are more than those of concrete specimen. The rubber particles degrade at a slow rate when compared to the other constituents in the concrete matrix resulting in fewer cracks in rubcrete cubes when compared to the concrete cubes [54]. Hence, the reduction in compressive strength is lower than the concrete cubes when exposed to acid attack, sulphate attack and marine water ingress. The polypropylene fibres deteriorate faster than rubber particles when exposed to a severe environment. But, rubber particles in polypropylene fibre-reinforced rubcrete deteriorate slowly in comparison with the rate of deterioration of the other material constituents. Hence, the weight loss of polypropylene fibre-reinforced rubcrete cubes is greater than that of rubcrete cubes. The ability of polypropylene fibres to bridge the gap between the materials helps in controlling the reduction in compressive strength when compared to rubcrete cubes when subjected to durability tests. Steel fibres deteriorated faster than the polypropylene fibres. This explains the greater reduction in weight of cubes when compared to the other mixes. But, the remaining steel fibre reinforcement in the matrix acts to hold the widening cracks and helps in improving the compressive strength of cubes. Thus, it can be observed from the results of durability studies that for both M 40 and M 60 grade concrete, steel fibre-reinforced rubcrete performs better than or at par with concrete mix with respect to its performance in withstanding sulphate attack, acid attack and degradation due to exposure to the marine environment. Though the water absorption and sorptivity of steel fibre-reinforced rubcrete mix are greater than those of normal concrete, their performance is within the specified permissible limits. Hence, it can be safely concluded that when it comes to the energy absorption capacity, for both M 40 and M 60 grade concretes, steel fibre-reinforced rubcrete performs significantly better than conventional concrete and it has the requisite durability to be used in severe environments.

Benefit-to-Cost Ratio

Table 13 provides the details of the unit cost incurred for the materials used in the study. 2 bar benders worked for 0.5 days to complete the bar bending of one beam. Table 14 presents the benefit-to-cost ratio M 40 and M 60 grade beams. For M 60 grade reinforced rubcrete beams, the benefit-to-cost ratio was 0.21 Nm/Rs more than the concrete beam. Improvements in energy absorbed/cost ratio of 1.08Nm/Rs and 2.1Nm/Rs, respectively, were noticed for M 40 grade polypropylene fibre and steel fibre-reinforced rubcrete beams. Enhancement in the energy absorption/cost ratio was 0.21 Nm/Rs for M 60 grade rubcrete beam. Increase in the energy absorption/cost ratio of 1.8 Nm/Rs and 2.89 Nm/Rs was seen for M 60 grade polypropylene fibre and steel fibre-reinforced rubcrete beams, respectively. From the results of benefit-to-cost ratio of M 40 and M 60 grade concrete, rubcrete and fibre-reinforced rubcrete beams, it was observed that the maximum energy absorbed/cost ratio was obtained for steel fibre-reinforced rubcrete beam with 0.75% steel fibres and 15% crumb rubber content.

Conclusions

To understand the behaviour of M 40 and M 60 grade beams subjected to impact loads, experimental and numerical studies were carried out on beams of size 100 × 150 × 1200 mm. Durability tests such as water absorption, sorptivity, marine attack, acid resistance and sulphate resistance were carried out on rubcrete and fibre-reinforced rubcrete mixes to assess the durability properties of rubcrete and fibre-reinforced rubcrete mixes when subjected to extreme conditions. The major conclusions from the above-mentioned studies are listed below.

(1) Numerical and experimental studies on fibre-reinforced rubcrete beams showed similar trends in energy absorption capacities and failure pattern.
(2) The energy absorption capacity of M 40 grade polypropylene fibre-reinforced rubcrete beam was 81% more than the energy absorption capacity of M 40 grade ordinary concrete beams. Improvement of 104% was noticed in the energy absorption capacity for M 60 grade polypropylene fibre-reinforced rubcrete when compared to the energy absorption capacity of M 60 grade ordinary concrete beams.
(3) Steel fibre-reinforced rubcrete beams of M 40 grade concrete showed 175% improvement in the energy absorption capacity when compared to the energy absorption capacity of ordinary concrete beams of M 40 grade. Enhancement of 183% in energy absorption for M 60 grade steel fibre-reinforced rubcrete beams was observed in comparison with the energy absorption capacity of ordinary concrete beams of M 60 grade.
(4) Maximum energy absorption/cost ratio was noticed for steel fibre-reinforced rubcrete beams with 0.75% steel fibres and 15% crumb rubber.
(5) Water absorption and sorptivity values for rubcrete and fibre-reinforced rubcrete specimens were higher than the reference specimen for both M 40 and M 60 grade concrete.
(6) When the specimens were exposed to 90 days of marine water, acid and sulphate environments, reduction in compressive strengths for rubcrete and fibre-reinforced rubcrete specimens was lesser than the decrease in compressive strengths for reference specimen.

The results presented in the studies indicate that among the eight variants of concrete, rubcrete and fibre-reinforced beams considered in the study, best energy absorption capacity and benefit-to-cost ratio were obtained for steel fibre-reinforced rubcrete beam in which 15% of the fine aggregates were replaced with crumb rubber and 0.75% of steel fibres. Hence, it can be effectively used for structures which have to resist impact/collision loads.

References

1. H. Sharma, S. Hurlebaus, P. Gardoni, Performance-based response evaluation of reinforced concrete columns subject to vehicle impact. Int. J. Impact Eng. **43**, 52–62 (2012). https://doi.org/10.1016/j.ijimpeng.2011.11.007
2. E. Severino, S. El-Tawil, Collision of vehicles with bridge piers. Comput. Fluid Solid Mech. **2003**(10), 637–640 (2003). https://doi.org/10.1016/B978-008044046-0.50156-1
3. P. Terndrup Pedersen, S. Valsgård, D. Olsen, S. Spangenberg, Ship impacts: bow collisions. Int. J. Impact Eng. **13**, 163–187 (1993). https://doi.org/10.1016/0734-743X(93)90091-K
4. J.J. Blok, L.H. Brozius, J.N. Dekker, The impact loads of ships colliding with fixed structures. In: *Proceedings of the Annual Offshore Technology Conference*. pp. 231–240 (1983)
5. A. Daniello, H.C. Gabler, Effect of barrier type on injury severity in motorcycle-to-barrier collisions in North Carolina, Texas, and New Jersey. Transp. Res. Rec. (2011). https://doi.org/10.3141/2262-14

6. Press Information Bureau of, India, G. of, India, M. of R.T.& H.: The ministry of road transport and highways has issued a notification increasing permissible truck axle load (2018)
7. R. Adland, H. Jia, S.P. Strandenes, The determinants of vessel capacity utilization: the case of Brazilian iron ore exports. Transp. Res. Part A Policy Pract. **110**, 191–201 (2018). https://doi.org/10.1016/j.tra.2016.11.023
8. E.R. Dahlen, R.C. Martin, K. Ragan, M.M. Kuhlman, Driving anger, sensation seeking, impulsiveness, and boredom proneness in the prediction of unsafe driving. Accid. Anal. Prev. **37**, 341–348 (2005). https://doi.org/10.1016/j.aap.2004.10.006
9. D.-J. Kim, S.-Y. Kwak, Evaluation of human factors in ship accidents in the domestic sea. J. Ergon. Soc. Korea. **30**, 87–98 (2011). https://doi.org/10.5143/jesk.2011.30.1.87
10. G. Goel, S.N. Sachdeva, Analysis of road accidents on NH-1 between RD 98 km to 148 km. Perspect. Sci. **8**, 392–394 (2016)
11. P. Antão, C. Guedes Soares, Causal factors in accidents of high-speed craft and conventional ocean-going vessels. Reliab. Eng. Syst. Saf. **93**, 1292–1304 (2008). https://doi.org/10.1016/j.ress.2007.07.010
12. T. Ngo, P. Mendis, A. Gupta, J. Ramsay, Blast loading and blast effects on structures—an overview. Electron. J. Struct. Eng. **7**, 76–91 (2007)
13. T.R. Naik, Sustainability of concrete construction. Pract. Period. Struct. Des. Constr. **13**, 98–103 (2008). https://doi.org/10.1061/(ASCE)1084-0680(2008)13:2(98)
14. M.M. Reda Taha, A.S. El-Dieb, M.A. Abd El-Wahab, M.E. Abdel-Hameed, Mechanical, fracture, and microstructural investigations of rubber concrete. J. Mater. Civ. Eng. **20**, 640–649 (2008). https://doi.org/10.1061/(ASCE)0899-1561(2008)20:10(640)
15. M.K. Batayneh, I. Marie, I. Asi, Promoting the use of crumb rubber concrete in developing countries. Waste Manag **28**, 2171–2176 (2008). https://doi.org/10.1016/j.wasman.2007.09.035
16. E. Ozbay, M. Lachemi, Compressive strength, abrasion resistance and energy absorption capacity of rubberized concretes with and without slag. Mater. Struct. Constr. **44**, 1297–1307 (2011). https://doi.org/10.1617/s11527-010-9701-x
17. A.O. Atahan, A.Ö. Yücel, Crumb rubber in concrete: static and dynamic evaluation. Constr. Build. Mater. **36**, 617–622 (2012). https://doi.org/10.1016/j.conbuildmat.2012.04.068
18. N. Ganesan, J. Bharati Raj, A.P. Shashikala, Flexural fatigue behavior of self compacting rubberized concrete. Constr. Build. Mater. **44**, 7–14 (2013). https://doi.org/10.1016/j.conbuildmat.2013.02.077
19. J. Wang, Q. Dai, R. Si, S. Guo, Investigation of properties and performances of Polyvinyl Alcohol (PVA) fiber-reinforced rubber concrete. Constr. Build. Mater. **193**, 631–642 (2018). https://doi.org/10.1016/j.conbuildmat.2018.11.002
20. J.C. Carroll, N. Helminger, Fresh and hardened properties of fiber-reinforced rubber concrete. J. Mater. Civ. Eng. **28**, 1–9 (2016). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001541
21. J.A.O. Barros, V.M.C.F. Cunha, A.F. Ribeiro, J.A.B. Antunes, Post-cracking behaviour of steel fibre reinforced concrete. Mater. Struct. **38**, 47–56 (2005). https://doi.org/10.1617/14058
22. A. Raj, P.J. Usman Arshad, P. Nagarajan, A.P. Shashikala, Fracture behaviour of fibre reinforced rubcrete. Mater. Sci. Forum (2019). https://doi.org/10.4028/www.scientific.net/MSF.969.80
23. C.X. Qian, P. Stroeven, Development of hybrid polypropylene-steel fibre-reinforced concrete. Cement. Concr. Res. **30**, 63–69 (2000)
24. A. Raj, P.J.U. Arshad, P. Nagarajan, A.P. Shashikala, Experimental investigation on the fracture behaviour of polypropylene fibre-reinforced rubcrete, in *Structural integrity assessment. Lecture notes in mechanical engineering*, ed. by R. Prakash, Kumar R. Suresh, A. Nagesha, G. Sasikala, A. Bhaduri (Springer, Singapore, 2020)
25. C. Hall, C. Hall, Water sorptivity of mortars and concretes: a review. Mag. Concr. Res. **41**, 51–61 (1989). https://doi.org/10.1680/macr.1989.41.147.51
26. J. Pitroda, F.S. Umrigar, Evaluation of sorptivity and water absorption of concrete with partial replacement of cement by thermal industry waste (Fly Ash). Int. J. Eng. Innov. Technol. **2**, 245–249 (2008)
27. F. Massazza, Pozzolana and Pozzolanic cements. In: *Lea's Chemistry of Cement and Concrete*, pp. 471–635 (2003). https://doi.org/10.1016/B978-075066256-7/50022-9
28. J.R. Mackechnie, M.G. Alexander, Exposure of concrete in different marine environments. J. Mater. Civ. Eng. **9**, 41–44 (1997). https://doi.org/10.1061/(ASCE)0899-1561(1997)9:1(41)
29. M. Regourd, Physico-chemical studies of cement pastes, mortars, and concretes exposed to sea water. In *ACI-International Concrete Abstracts Portal*, pp. 63–82. American Concrete Institute (1980)
30. N.I. Fattuhi, B.P. Hughes, The performance of cement paste and concrete subjected to sulphuric acid attack. Cement Concr. Res. **18**(4), 545–553 (1988)
31. C. Lawrence, Sulphate attack on concrete. Mag. Concr. R. **42**, 93–96 (1990). https://doi.org/10.1680/macr.54.4.301.38805
32. T.G. Nijland, J.A. Larbi, Microscopic examination of deteriorated concrete. Non-destructive Eval. Reinf. Concr. Struct. Deterior. Process. Stand. Test Methods (2010). https://doi.org/10.1533/9781845699536.2.137
33. Research Designs and Standards Organisations: Indian Railway Standard Specification for Pre-Tensioned Prestressed Concrete Sleepers for Broad Gauge and Metre Gauge (T-39-85) (2011)
34. Indian Roads Congress: Standard Specifications and Code of Practice for Road Bridges.IRC: 6-2016 (2016)
35. Bureau of Indian Standards: Coarse and Fine Aggregate for Concrete-Specification (Third Revision). IS 383 2016 1. 19, (2016)
36. A. Raj, P. Nagarajan, A.P. Shashikala, Application of fiber reinforced rubcrete for crash barriers. J. Mater. Civ. Eng. (2020). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003454
37. A. Raj, P. Nagarajan, A.P. Shashikala, Investigations on fiber reinforced rubcrete for railway sleepers. ACI Struct. J. (2020). https://doi.org/10.14359/51724679
38. Bureau of Indian Standards: Method of Tests for Strength of Concrete (2004). https://doi.org/10.3403/02128947
39. ACI (American Concrete Institute), Measurement of Properties of Fiber Reinforced Concrete.ACI 544.2R-11 (1996)
40. A. Badr, A.F. Ashour, A.K. Platten, Statistical variations in impact resistance of polypropylene fibre-reinforced concrete. Int. J. Impact Eng. **32**, 1907–1920 (2006). https://doi.org/10.1016/j.ijimpeng.2005.05.003
41. M. Mamun, V. Bindiganavile, Drop-weight impact response of fibre reinforced cement based foams. Int. J. Prot. Struct. **1**, 409–424 (2010)
42. W. Zhang, S. Chen, Y. Liu, Effect of weight and drop height of hammer on the flexural impact performance of fiber-reinforced concrete. Constr. Build. Mater. **140**, 31–35 (2017). https://doi.org/10.1016/j.conbuildmat.2017.02.098
43. D.R. Rilem, RILEM TC-50 FMC: Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Mater. Struct. Constr. **8**, 285–296 (1985). https://doi.org/10.1007/BF00962380
44. A. Raj, P.J. Usman Arshad, P. Nagarajan, A.P. Shashikala, Experimental investigation on the fracture behaviour of polypropylene fibre-reinforced rubcrete (2020). https://doi.org/10.1007/978-981-13-8767-8_28

45. Bureau of Indian Standards: Method of test for determination of water absorption, apparent specific gravity and porosity of natural building stones (1974)
46. D.P. Bentz, M.A. Ehlen, C.F. Ferraris, J.A. Winpigler, Service life prediction based on sorptivity for highway concrete exposed to sulfate attack and freeze-thaw conditions. FHWA-RD-01, 62 (2002)
47. ASTM International: Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes., West Conshohocken, USA (2013)
48. American Society for Testing and Materials: Standard practice for the preparation of substitute ocean water. ASTM International (2013)
49. E. Hewayde, E. Allouche, G. Nakhla, Experimental investigations of the effect of selected admixtures on the resistance of concreteto sulfuric acid attack. New Pipeline Technol. Secur. Saf. pp. 504–513 (2004)
50. T. Ikumi, I. Segura, S.H. Cavalaro, Effects of biaxial confinement in mortars exposed to external sulfate attack. Cem. Concr. Compos. **95**, 111–127 (2019)
51. A. Chabrelie, U. Mueller, K. Scrivener, Mechanisms of degradation of concrete by external sulfate ions under laboratory and field conditions (2011)
52. J.C. Walraven, Model Code 2010-final draft. fib Fédération internationale du béton (2012)
53. K. Bisht, P.V. Ramana, Evaluation of mechanical and durability properties of crumb rubber concrete. Constr. Build. Mater. **155**, 811–817 (2017). https://doi.org/10.1016/j.conbuildmat.2017.08.131
54. B.S. Thomas, R.C. Gupta, V.J. Panicker, Recycling of waste tire rubber as aggregate in concrete: durability-related performance. J. Clean. Prod. **112**, 504–513 (2016). https://doi.org/10.1016/j.jclepro.2015.08.046