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Effect of red mud filler on mechanical and buckling characteristics of coir fibre-reinforced polymer composite

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Abstract Red mud produced as by-product in Bayer's process for alumina production is posing severe environmental challenge in its disposal. Present work describes using this environmental pollutant as filler in combination with coir fibre using polyester resin for composite production. Tensile properties, flexural properties, compressive properties, hardness and density of coir polymer composites with and without red mud filler were evaluated experimentally. Subsequently, buckling analysis of the prepared composite was also done experimentally and using finite element method at different grid size and for different number of elements to establish the grid independence of obtained results. It has been observed that compressive strength, hardness and density of the prepared composite improved with addition of red mud as filler. This may be attributed to metallic oxides present in chemical composition of red mud. Addition of the filler had a negative effect on tensile and buckling properties as the load cannot be transferred effectively from fibre to resin. Interestingly, it has been observed that composite plates with 20 % fibre gave optimum combination of various properties. The main aim of this work was to study the effect of red mud filler on the mechanical properties and buckling strength of the prepared composites leading to development of a novel low-cost, light-weight composite material using an environmental pollutant which can be used for light-weight structural application.

Keywords Red mud · Coir fibre · Polyester resin · Mechanical properties · Buckling analysis

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Introduction

Technical advancements in field of composites have made it possible to manufacture laminated composite materials possessing unique customised properties such as high strength/stiffness, low weight, better corrosion resistance, resistance to heat and environmental degradation, customised properties based on varying stacking pattern, etc. This has resulted in increased application of such materials in variety of structures including aerospace, civil infrastructure, marine, etc. [1]. Natural fibres like jute, coir, bagasse, banana, etc., are nowadays favoured than conventional glass, aramid and other artificial fibres owing to their light weight, abundance, low cost and good mechanical properties [2, 3].

The natural fibre composites are readily used in automobile industries, military application, construction industries, furniture industries, low-cost housing, etc.

The higher cost of composites is the only factor hampering its use in majority of industrial application in spite of possessing customised properties specific to given application. Some researchers have found that adding low cost and readily available filler is the easiest way to bring down the cost of composites. However, mechanical properties of the composites should not be affected adversely in the attempt of reducing the cost. Therefore, fillers are added firstly to improve the mechanical and tribological properties and secondly to reduce the cost of the components [4]. Around 30 million tons/year of red mud (waste material) is produced during aluminium production by Bayer's process. The intensity of this problem lies in its accumulation rate which is around 30 million tons/year. Disposal of red mud is a severe problem as it is highly alkaline and produced in huge quantities [5].

Because of leakage of alkaline red mud liquor into the ground there is probability of ground water contamination. Also it can cause dust pollution in arid regions as it is mostly in form of fine dust with particle size of order of 300 mesh. Bauxite processing industries in Jamaica produces red mud which is sufficient to bury 700 football grounds and their goal posts [6]. Direct disposal of red mud into sea creates problem to marine flora and fauna and also reacts with magnesium of sea water and creates additional finely divided solids changing the physico-chemical conditions of the area. Therefore, an attempt was made here to develop cost-effective polymer composites having excellent mechanical properties using red mud as filler.

Misra et al. [7] discussed the processing and evaluated the mechanical properties of coir polyester composites at various percentages of the coir fibre, experimentally. Also the effect of continuous and discontinuous distribution of coir fibre in polyester resin has been studied thoroughly and its effect on mechanical properties has been determined. Saxena et al. [8] have used red mud and fly ash as filler in combination with natural fibres like sisal and jute to develop composites. The mechanical properties of newly developed composite were found much superior than the conventional wood/particle woods. Hossein et al. [9] studied the thermal and mechanical behaviour of maleic anhydride grafted polypropylene/silica composites at various sizes of reinforcements. Addition of silica particles leads to improvement in crystallisation rate, crystallinity percentage, Young's modulus, strength and thermal stability of MA-g-PP composites. Kilic et al. [10] concluded that various construction products produced from red mud do not produce any harmful effects and can be used safely complying with the requirement of regulation on regular storage of waste in Turkey after performing series of environment compliance tests on them.

Chowdhury et al. [11] suggested the use of various natural fibre composite using fibres like jute, rice husk, etc., for developing sustainable low-cost housing materials in countries like India where concrete or steel housing is expensive. Adedeji et al. [12] focused on use of composite panels for sustainable housing provision in Nigeria. They developed composite panel using agricultural waste, i.e., cement reinforced with palm kernel fibre, a by-product of oil palm for cost-efficient building panels for walls. Since the developed composite panel in the present work can be used for this kind of structural application in earthquake-prone areas and developing countries, it is necessary to check its stability under axial loading. Thus, buckling analysis of prepared composite plates was also done to achieve the same objective. The stability of structures under axial loading has been investigated by some researchers [13, 14].

Jayaram Mohanty et al. [15] studied the influences of various parameters such as delamination area, fibre orientations, number of layers, aspect ratios on the buckling behaviour of single and multiple delaminated woven roving glass/epoxy composite plates and concluded that these parameters have paramount influence on the buckling behaviour of delaminated plate. Baba et al. [16] studied the influence of various boundary conditions like clamped, pinned, etc., on the buckling load for rectangular E glass/

Fig. 1 Composite plates without red mud

Fig. 2 Composite plates with red mud

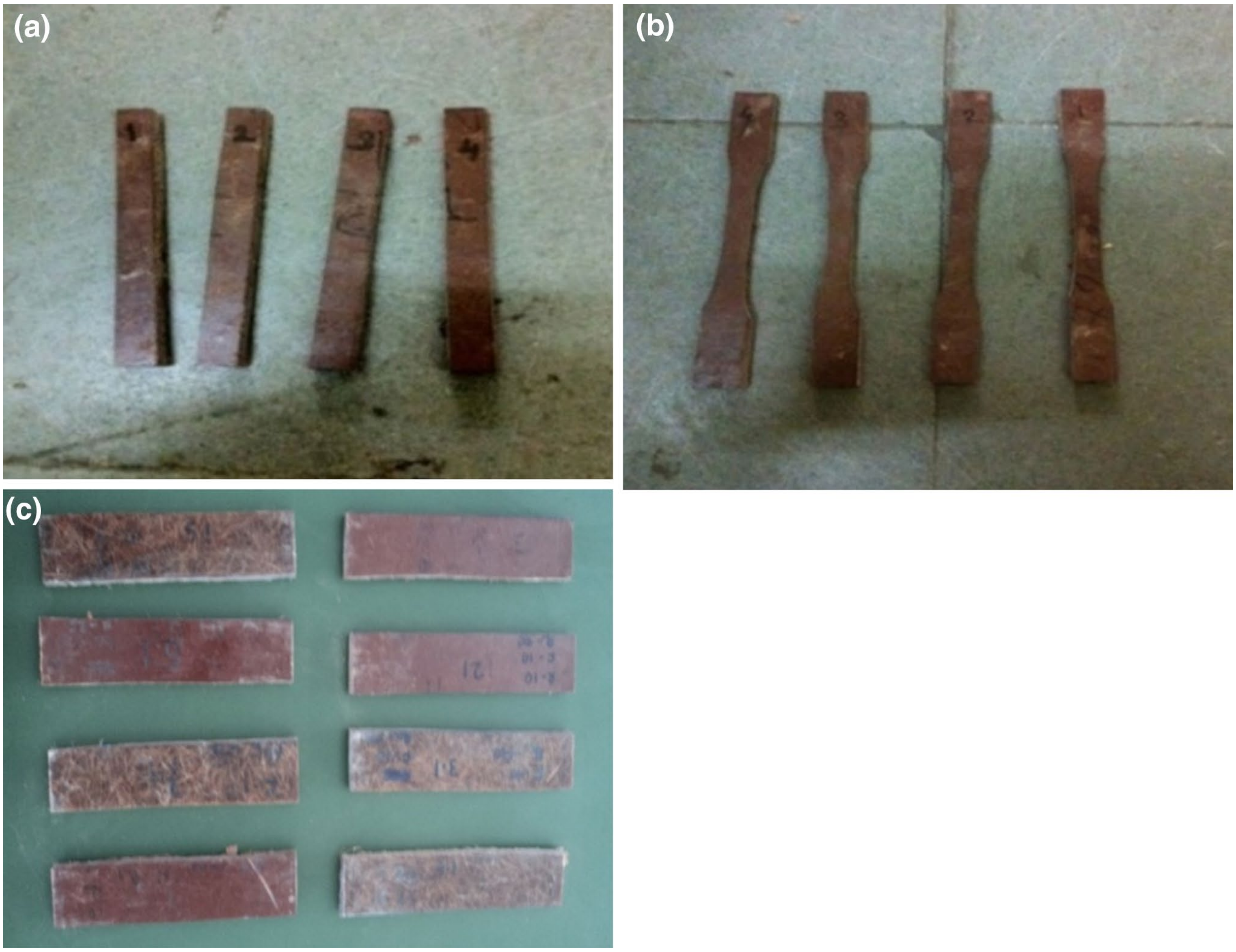

Fig. 3 Samples cutting for flexural testing (**a**), tensile testing (**b**), and compressive testing (**c**)

epoxy plates of various geometries. Qablan et al. [17] studied the effect of cut-out size, cut-out location, fibre orientation angle and type of loading on the buckling load of square cross-ply laminated plates with circular cut-outs. They concluded that the effect of cut-out size is remarkable in case of shear loading in comparison to axial loading.

Moita et al. [18] developed a finite element model using eight-node quadrilateral element for linear buckling analysis of laminated composite structures. They studied the effect of various geometrical parameters, material properties, ply orientation, etc., on buckling load. The same element was later used to study the vibration and buckling response of composite structures for various geometries [19].

Onkar et al. [20] developed a generalised layer-wise stochastic finite element formulation for the buckling analysis of both homogeneous and laminated plates with random material properties.

It can be seen from available literature that various researchers have tried to study mechanical properties of various fibre resin combinations, but majority of them have not tried to examine the effect of particulate filler on mechanical and structural properties of composites. Also exhaustive work has not been done on buckling analysis of the composites. Therefore, the objectives of the present work were to study the effect of fibre and filler contents on mechanical properties of coir polyester composite. Moreover, buckling analysis of the prepared composites has been done experimentally as well as using ANSYS to determine its buckling strength.

Experimental

Materials and methods

This section describes the details of processing of the composites and the experimental procedures followed for their mechanical properties evaluation. The raw materials used in this work are as follows:

- Coir fibre obtained from Central Coir Board Ahmedabad, India. The fibre was used in random chopped form with uniform length of 50 mm. The diameter of fibre varies from 0.1 to 0.3 mm with relative density of 1.12–1.15.
- Red mud obtained from HINDALCO Belgaum, India. The red mud was used in dry powdered form with particle size 70–90 µm, having bulk density in range of 1.36–1.6 g/cc.
- Polyester resin from Rajkot, India. Unsaturated isophthalic polyester resin with density of 1.35 gm/cc and elastic modulus 3.23 GPa was used as matrix material. Methyl ethyl ketone peroxide (MEKP) was used as hardener and cobalt naphthalene as accelerator.

Material preparation

A wooden mould of dimension 250 × 250 × 10 mm was used for casting the composite plate. In the present investigation four composites plates were manufactured without red mud and another four composites plates were manufactured with red mud. Rachchh et al. [21] have studied the effect of varying filler content on mechanical properties of coir red mud composite and concluded that the best properties are available with 10 % filler loading.

Thus, in this work for composite plates with red mud, 10 % red mud content was fixed and fibre content varied as 10, 15, 20, and 25 %, respectively. In this case, red mud, polyester resin, hardener and accelerator were thoroughly mixed with gentle stirring to minimise air entrapment. But, resin, accelerator and hardener were thoroughly mixed in case of composite samples without red mud. Then by using hand layup technique, first layer of slurry was prepared. Above that chopped coir fibres are arranged and then slurry is poured, and so on. This procedure was followed until the required thickness was achieved. For quick and easy removal of composite plates, a mould release spray was applied at the inner surface of the mould. Care was taken to avoid formation of air bubbles. Pressure was then applied from the top and the mould was allowed to cure at room temperature for 24 h. This procedure was adopted for preparation of composites plates. After 24 h the plates were taken out of the mould, cut into different sizes for further experimentation. Figures 1 and 2 show composite plates with and without red mud, respectively.

Sample preparation

Five samples were prepared from each composition plate according to relevant ASTM standards and average readings of properties were considered for results. For density measurement, samples were prepared according to ASTM-792 while for flexural, tensile and compressive properties samples were prepared according to ASTM D-790-10, ASTM D-638 and ASTM D-695, respectively. For barcol hardness ASTM D-2583 was followed. The samples for flexural, tensile and compressive are shown in Fig. 3a–c, respectively. All the testing was carried out as per the relevant ASTM standards.

Fig. 4 Buckling test setup

Experimental buckling analysis

Eight specimens of different compositions having dimension of 50 × 250 × 10 mm were used to determine the buckling loads of the specimens. The specimens were loaded in axial compression using Aimil (AIM 302, India) compressive testing machine of 100 tonne capacity as shown in Fig. 4. A dial gauge was mounted at the centre of the specimen to observe the lateral deflection. For axial loading, the test specimens were placed between the two extremely stiff machine heads, of which the lower one was fixed during the test, whereas the upper head was moved downwards by servo hydraulic cylinder. All plates were loaded at constant cross-head speed of 1 mm/min. As the load was increased, the dial gauge needle started moving, and at the onset of buckling there was a sudden large movement of the needle. The load corresponding to this point is taken as the buckling load of the specimen. Test specimen after buckling is shown in Fig. 5.

Fig. 5 Test specimen under buckling

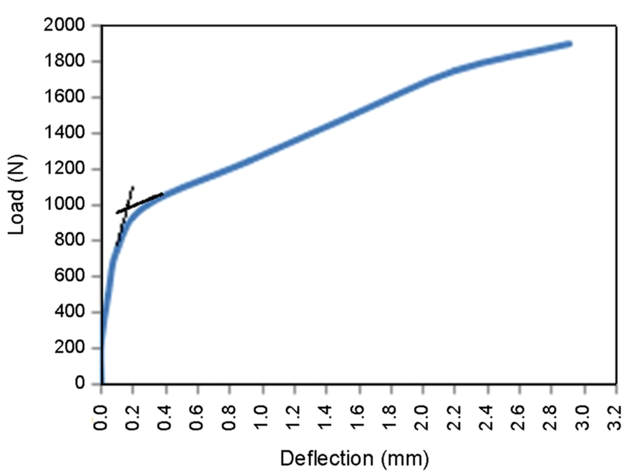

Fig. 6 Load versus deflection graph (*R* 90 %, *F* 10 %, *RM* 0 %)

Load versus deflection graphs

This type of graph can be used to determine experimental buckling load as shown by Yang et al. [22] and Mohtaram

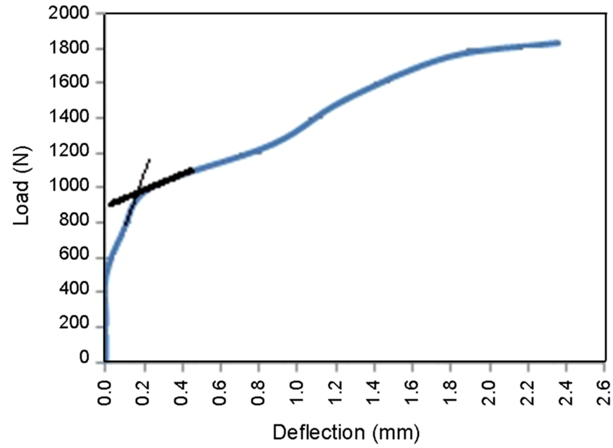

Fig. 7 Load versus deflection graph (*R* 90 %, *F* 10 %, *RM* 10 %)

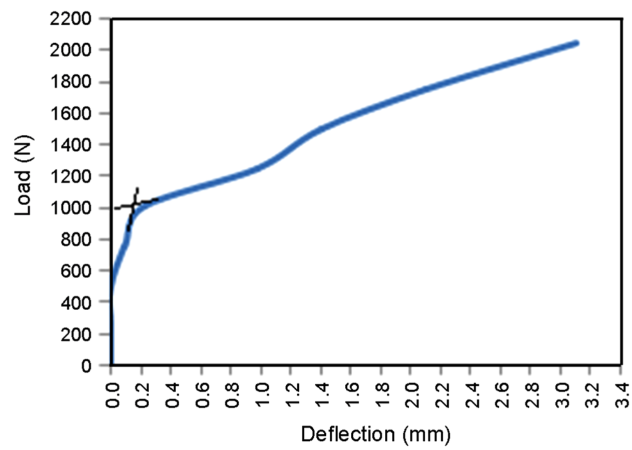

Fig. 8 Load versus deflection graph (*R* 85 %, *F* 15 %, *RM* 0 %)

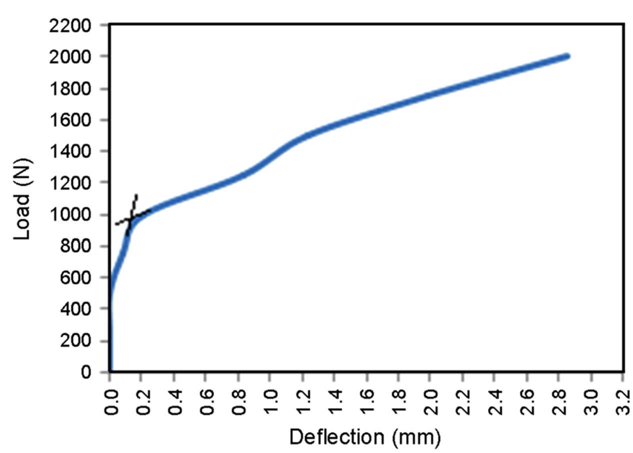

Fig. 9 Load versus deflection graph (*R* 75 %, *F* 15 %, *RM* 10 %)

et al. [23]. The load vs. deflection curves for eight different samples are shown in Figs. 6, 7, 8, 9, 10, 11, 12 and 13. It can be seen from the figures that below a certain load, load

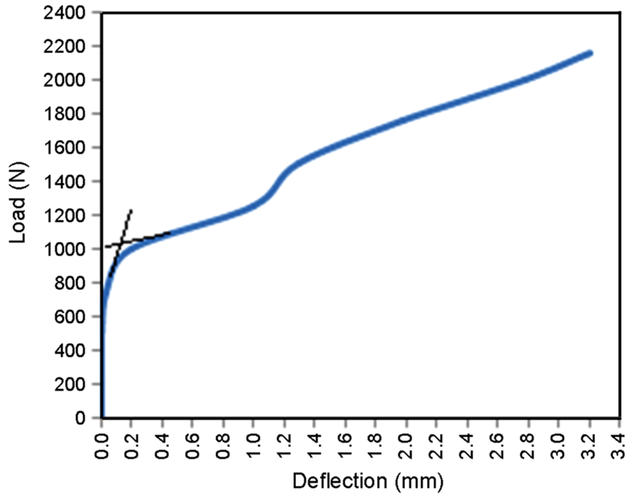

Fig. 10 Load versus deflection graph (*R* 80 %, *F* 20 %, *RM* 0 %)

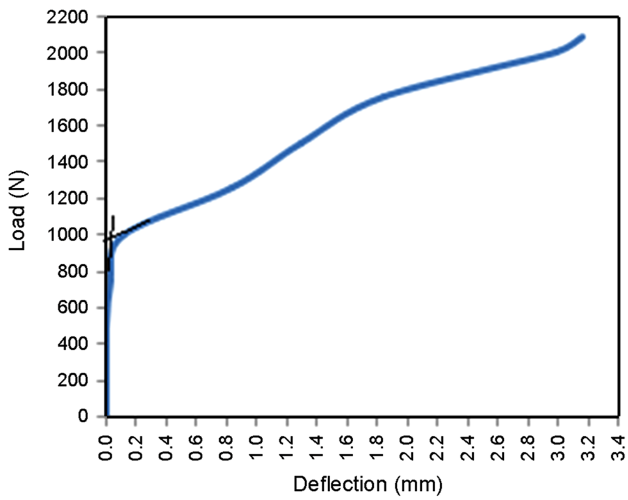

Fig. 11 Load versus deflection graph (*R* 70 %, *F* 20 %, *RM* 10 %)

versus deflection followed a linear relationship. However, at a particular load, the deflection suddenly increased and deviated from the linear relation. This load is taken as the critical buckling load and is determined from the intersection of two tangents drawn from the pre-buckling and post-buckling regions.

Finite element analysis

ANSYS 12.1 was used to analyse the critical buckling load of composite plates of the same sizes and different material composition. The dimensions of the specimen were 50 × 250 × 10 mm in length, width and thickness. The plate was modelled using 20-node hexahedral element using coarse, medium and fine grid as given in Table 1. Hex

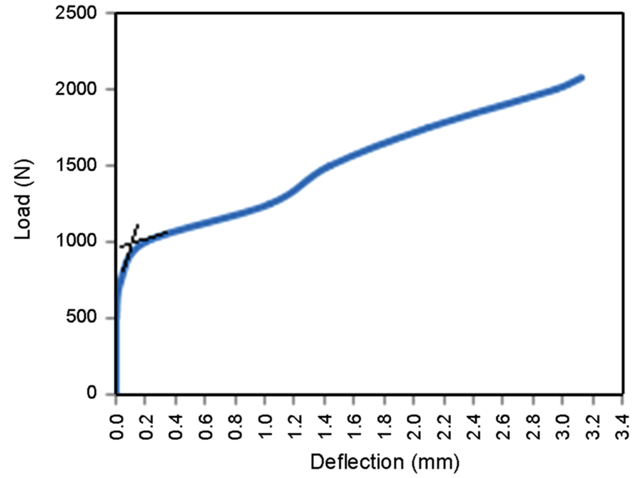

Fig. 12 Load versus deflection graph (*R* 75 %, *F* 25 %, *RM* 0 %)

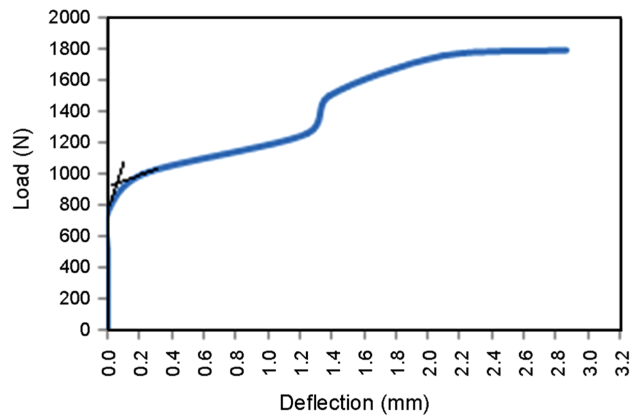

Fig. 13 Load versus deflection graph (*R* 65 %, *F* 25 %, *RM* 10 %)

20 is the most common element used for simple flat geometries. Figure 14 shows a typical meshing. The applied boundary condition and load for linear buckling analysis is as shown in Fig. 15. Buckling analysis results of different material composition plates are as shown in Figs. 16, 17, 18, 19, 20, 21, 22 and 23.

Results and discussion

Experimental buckling load was found lower than the one theoretically obtained from ANSYS [23]. The reason may be due to the presence of certain imperfections like voids, crack, etc., created due to improper bonding of fibre and resin at the time of manufacturing of composite plates. Also, buckling load is found lower in case of plates with red mud due to red mud particles occupying interstitial position between matrix and fibres resulting into stress concentration. This is shown in Table 1.

Table 1 Experimental and theoretical buckling loads

Sl. no.	Material composition (%)	Buckling load (*N*) experimentally	Buckling load (N) (using ANSYS)		
			Coarse grid	Medium grid	Fine grid
			Nodes = 683 Elements = 80	Nodes = 3909 Elements = 640	Nodes = 15189 Elements = 2856
1.	Resin: 90 Coir fibre: 10 Red mud: 0	990	1208.7	1202.9	1202.5
2.	Resin: 80 Coir fibre: 10 Red mud: 10	980	1174.8	1169.1	1168.7
3.	Resin: 85 Coir fibre: 15 Red mud: 0	1020	1295.6	1289.4	1289
4.	Resin: 75 Coir fibre: 15 Red mud: 10	990	1235.9	1229.9	1229.5
5.	Resin: 80 Coir fibre: 20 Red mud: 0	1050	1344.5	1338.1	1337.6
6.	Resin: 70 Coir fibre: 20 Red mud: 10	980	1168	1162.4	1162
7.	Resin: 75 Coir fibre:25 Red mud: 0	995	1317	1311	1310.6
8.	Resin: 65 Coir fibre: 25 Red mud: 10	920	1018	1013.7	1013.4

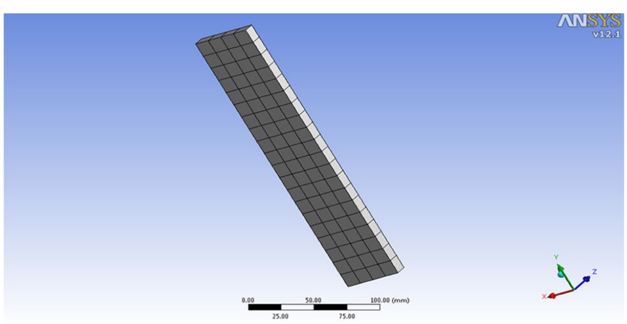

Fig. 14 Meshing of the composite plate

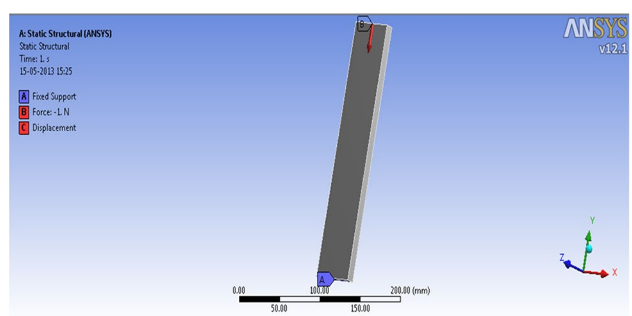

Fig. 15 Load and fixed support of the composite plate

Table 1 also clearly shows the effect of grid size on buckling load of composite plates. Grid size is one of the most important parameters in deciding the accuracy of any finite element formulation. It can be seen from the Table 1 that the deviation in the values of buckling loads for various grid size is less than 0.5 % which justifies the use of coarse grid for this analysis.

In Figs. 24, 25, 26, 27, 28, 29 and 30 for defining composition of plates R stands for resin, F means fibre and RM shows red mud. Also the digit next to it shows its content in percentage of overall composition.

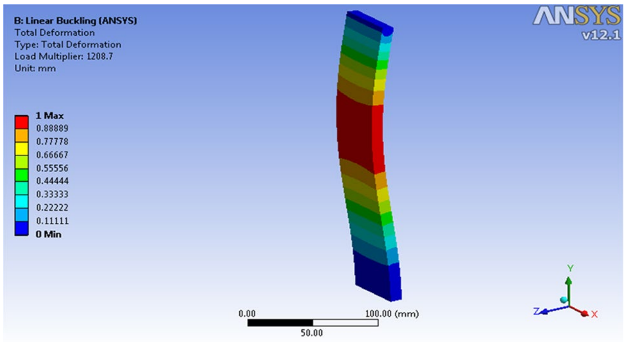

Fig. 16 Buckling load of the composite plate (*R* 90 %, *F* 10 %, and *RM* 0 %)

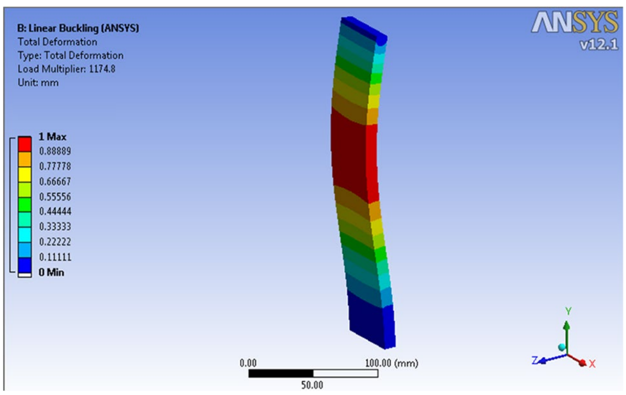

Fig. 17 Buckling load of the composite plate (*R* 80 %, *F* 10 %, and *RM* 10 %)

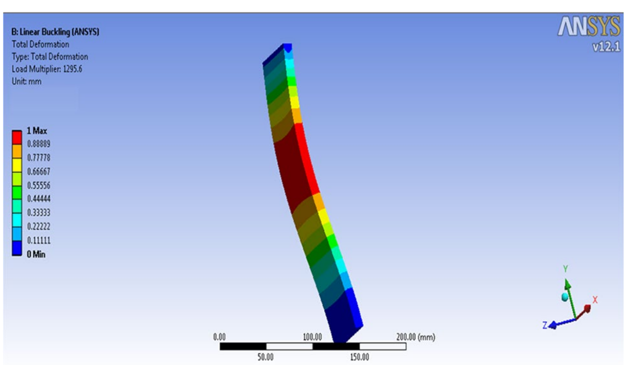

Fig. 18 Buckling load of the composite plate (*R* 85 %, *F* 15 %, and *RM* 0 %)

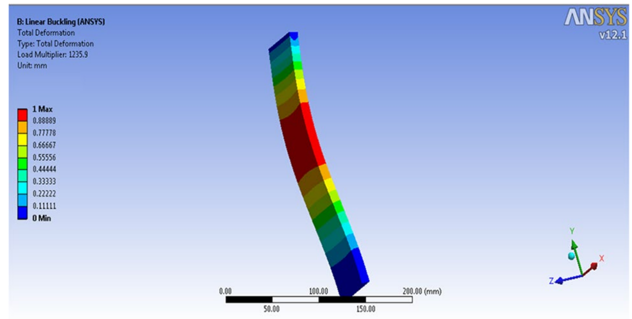

Fig. 19 Buckling load of the composite plate (*R* 75 %, *F* 15 %, and *RM* 10 %)

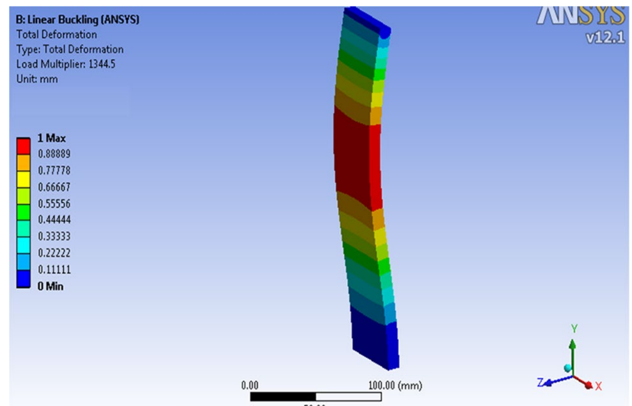

Fig. 20 Buckling load of the composite plate (*R* 80 %, *F* 20 %, and *RM* 0 %)

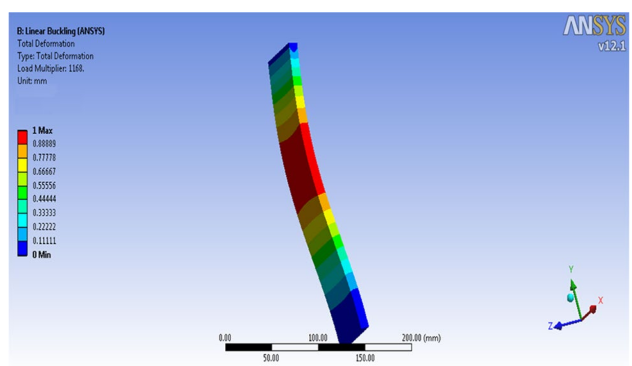

Fig. 21 Buckling load of the composite plate (*R* 70 %, *F* 20 %, and *RM* 10 %)

Figure 24 shows the tensile stress of randomly distributed coir fibre-reinforced polyester composites at various percent of material compositions plotted from the data in Table 2. From Fig. 24, it is seen that tensile stress increased initially and then decreased. Particle loading and its size, interfacial adhesion between particle, fibre and matrix significantly affect the strength of the composite. However, for composites containing well-bonded particles, addition of particles to the polymer will lead to an increase in strength of the composites. Thus, due to the good bonding of red

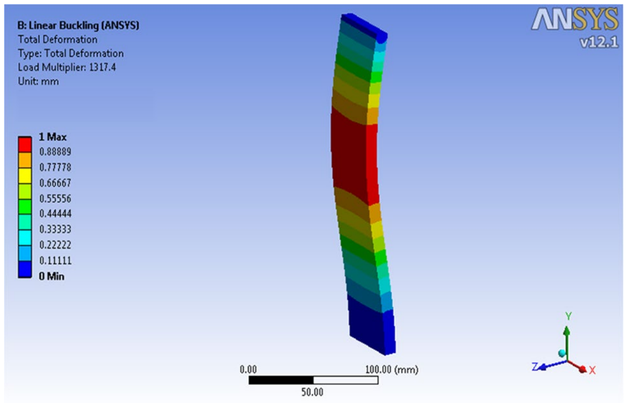

Fig. 22 Buckling load of the composite plate (*R* 75 %, *F* 25 %, and *RM* 0 %)

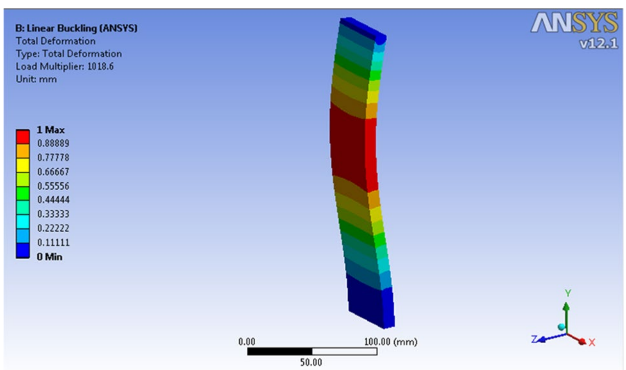

Fig. 23 Buckling load of the composite plate (*R* 65 %, *F* 25 %, and *RM* 10 %)

mud filler particles with matrix, the tensile strength of composites increased with rise in the fibre content up to 20 %. The slight decrease in tensile strength with addition of red mud filler was due to the poor adhesion between the fibre, filler and the matrix as without proper adhesion at higher loads, reinforcements promote void formation resulting into reduction in tensile strength. Best result was observed at 20 % of fibre without red mud, subsequently the load was not transferred from fibre to resin. Similar set of results were also obtained by Biswas et al. [24, 25] in their experiment on studying tribological properties of red mud composites, where addition of red mud leads to decrease in tensile strength, tensile modulus and increase in hardness of composite material.

Tensile modulus is directly related to the stiffness. If tensile modulus increases, then stiffness increases and vice versa. It can be seen from Fig. 25 that tensile modulus increased with increasing fibre content up to 20 % after which it decreased. The reason for the decrease is that when fibre

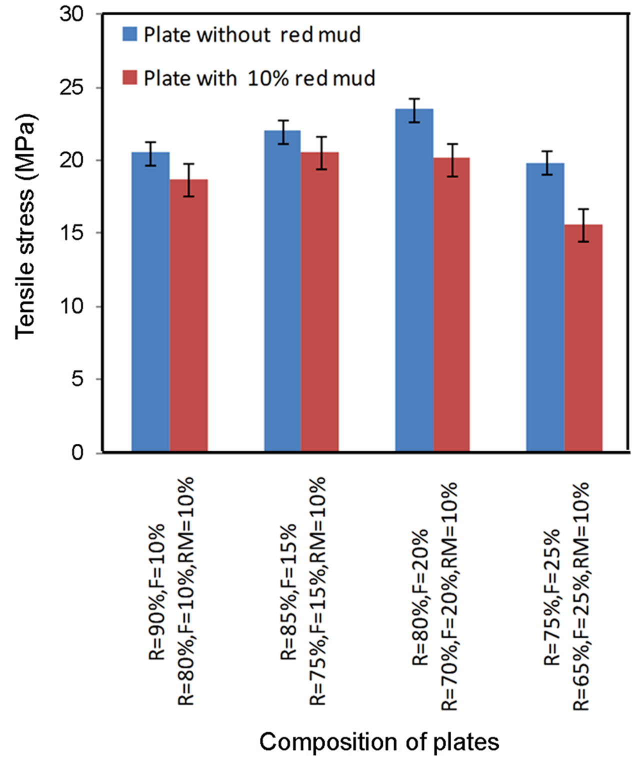

Fig. 24 Tensile stress at various percentage of the material composition

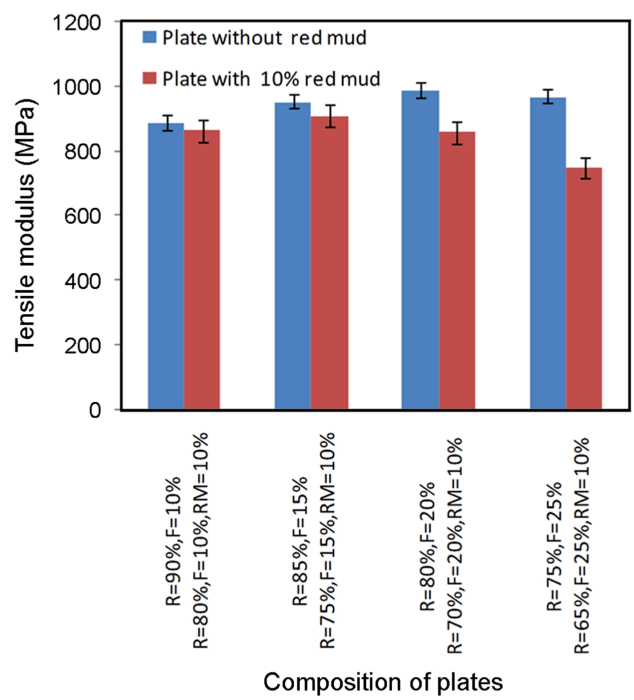

Fig. 25 Tensile modulus at various percentage of the material composition

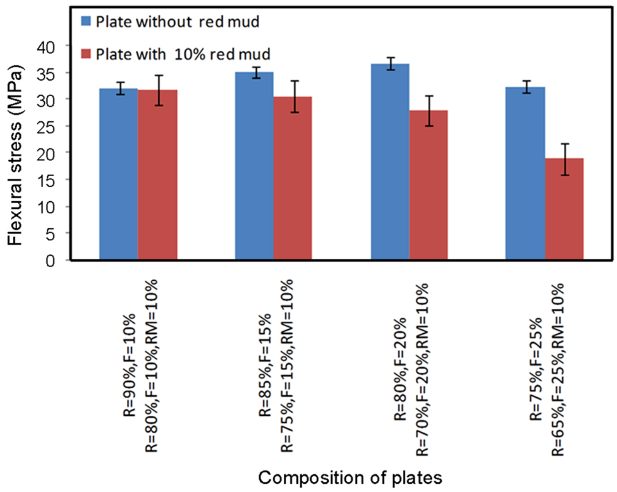

Fig. 26 Flexural stresses at various percentage of the material composition

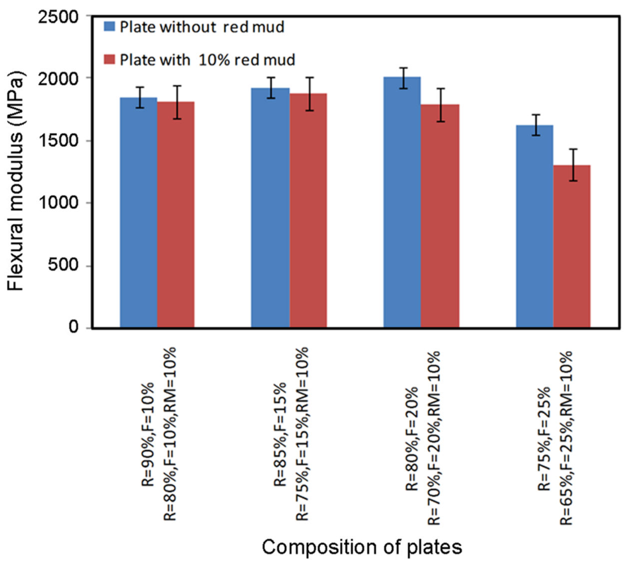

Fig. 27 Flexural modulus at various percentage of the material composition

content was increased beyond 20 %, the resin was insufficient to wet the fibre as a result of which the load could not be effectively transferred from fibre to resin. Also adding red mud content to the plate led to slight reduction in tensile modulus. When the bonding between the particles and matrix was poor, the stress transfer at the particle/polymer interface was insufficient. Therefore, discontinuity in the form of debonding existed because of non-adherence of particles to polymer particularly after 20 % fibre content which led to decrease in modulus afterwards. This is shown in Fig. 25.

When the percentage of coir fibre increased, the flexural modulus also increased. It is directly proportional to

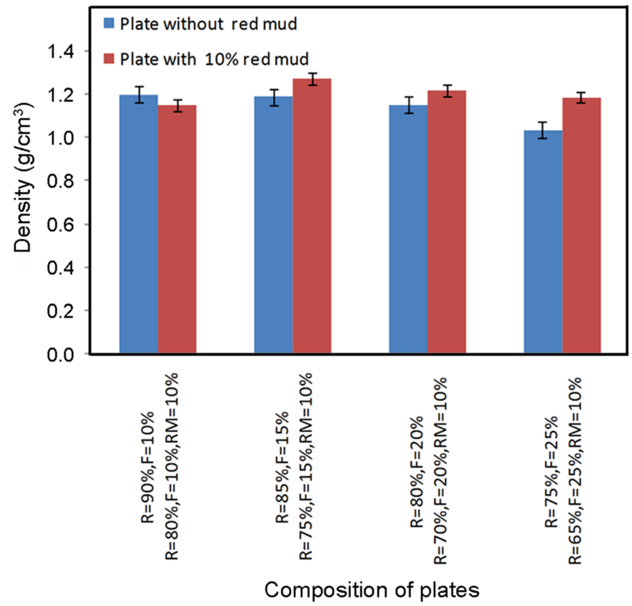

Fig. 28 Density at various percentage of the material composition

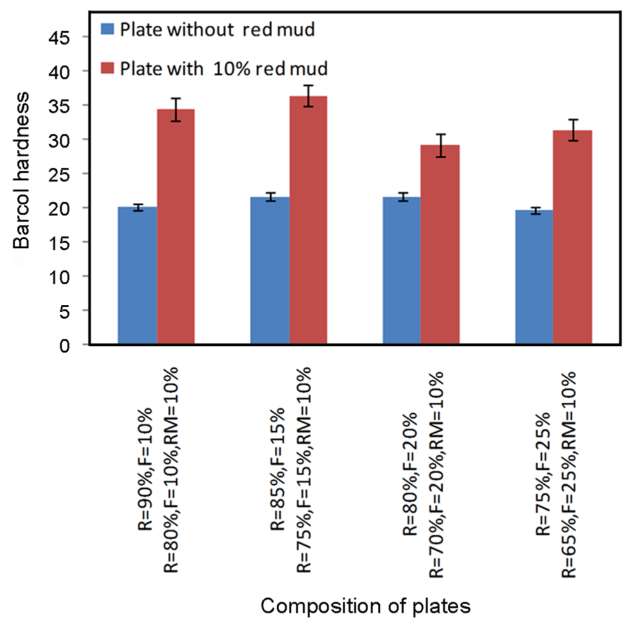

Fig. 29 Hardness at various percentage of the material composition

the flexural stress. Therefore, flexural stress also increased. The reason for decrease in flexural properties after 20 % fibre content again was the insufficiency of resin to cover up the fibre leading to pores, voids, etc. The reduction in the flexural strengths of the composites with red mud content was probably caused by an incompatibility of the particulates and the polyester matrix leading to poor interfacial bonding. The lower values of flexural properties may also be attributed to fibre-to-fibre interactions, voids, and

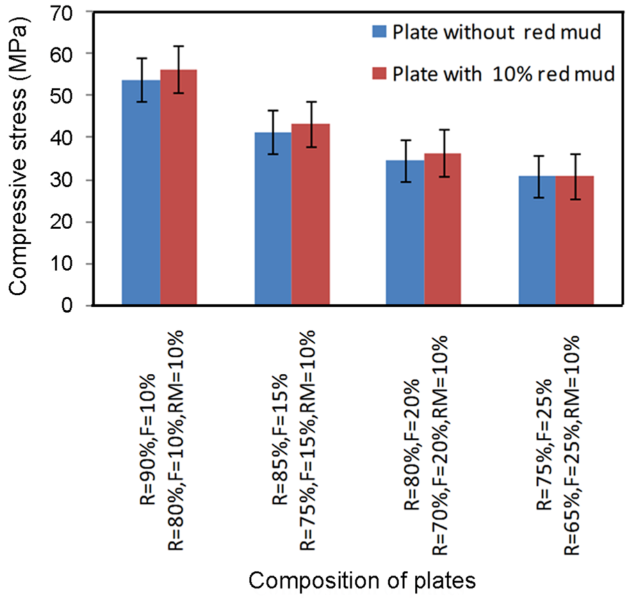

Fig. 30 Compressive stress at various percentage of the material composition

dispersion problems. This is shown in Figs. 26 and 27. The value of flexural stress is shown in Table 3.

Density of coir polyester composite is much lower than any other artificial fibre composite which clearly shows its utility as light-weight structural application. Density is higher in case of red mud content plate as it comprises iron, titanium, and the silica part of the parent ore along with other minor constituents. This is shown in Fig. 28. The values of density, barcol hardness and compressive stress are presented in Table 4.

Barcol hardness values were increased by adding the percentage of red mud in the plates. After that it would decrease due to debonding. As red mud contains heavy particles along with metal oxides like Fe_2O_3, Al_2O_3, SiO_2, etc., it imparts better hardness to the composite as shown in Fig. 29.

Addition of red mud led to improvement in compressive strength of composite due to inherent good compressive property of heavy red mud particles along with other metallic oxides present in it. Also, it made the composite useful in high load-bearing applications. This is clearly

Table 2 Tensile properties of randomly distributed coir polyester composites

Sl. no.	Material composition (%)	Tensile stress in MPa	Tensile strain	Tensile modulus
1.	Resin: 90 Coir fibre: 10 Red mud: 0	20.5	0.023034	890
2.	Resin: 80 Coir fibre: 10 Red mud: 10	18.7	0.021618	865
3.	Resin: 85 Coir fibre: 15 Red mud: 0	22	0.023061	954
4.	Resin: 75 Coir fibre: 15 Red mud: 10	20.5	0.022527	910
5.	Resin: 80 Coir fibre: 20 Red mud: 0	23.4	0.023636	990
6.	Resin: 70 Coir fibre: 20 Red mud: 10	20.1	0.023372	860
7.	Resin: 75 Coir fibre: 25 Red mud: 0	19.8	0.020412	970
8.	Resin: 65 Coir fibre: 25 Red mud: 10	15.6	0.0208	750

Table 3 Flexural properties of randomly distributed coir polyester composites at various percentages of material compositions

Sl. no.	Material composition (%)	Flexural stress in (MPa)	Flexural strain	Flexural modulus
1.	Resin: 90 Coir fibre: 10 Red mud: 0	32.14	0.017372973	1850
2.	Resin: 80 Coir fibre: 10 Red mud: 10	31.8	0.017520661	1815
3.	Resin: 85 Coir fibre: 15 Red mud: 0	35.12	0.018196891	1930
4.	Resin: 75 Coir fibre: 15 Red mud: 10	30.7	0.016286472	1885
5.	Resin: 80 Coir fibre: 20 Red mud: 0	36.75	0.018283582	2010
6.	Resin: 70 Coir fibre: 20 Red mud: 10	28	0.015598886	1795
7.	Resin: 75 Coir fibre: 25 Red mud: 0	32.4	0.019828641	1634
8.	Resin: 65 Coir fibre: 25 Red mud: 10	19.03	0.014471483	1315

Table 4 Barcol hardness, density and compressive of randomly distributed coir polyester composites at various percentages of material compositions

Sl. no.	Material composition	Density (kg/m^3)	Barcol hardness	Compressive stress (MPa)
1.	Resin: 90 Coir fibre: 10 Red mud: 0	1.2009	20.25	53.94
2.	Resin: 80 Coir fibre: 10 Red mud: 10	1.1499	34.5	56.42
3.	Resin: 85 Coir fibre: 15 Red mud: 0	1.1903	21.75	41.54
4.	Resin: 75 Coir fibre: 15 Red mud: 10	1.2728	36.5	43.40
5.	Resin: 80 Coir fibre: 20 Red mud: 0	1.1504	21.75	34.72
6.	Resin: 70 Coir fibre: 20 Red mud: 10	1.2176	29.25	36.58
7.	Resin: 75 Coir fibre: 25 Red mud: 0	1.0339	19.75	31.00
8.	Resin: 65 Coir fibre: 25 Red mud: 10	1.188	31.5	31.00

Table 5 Effect of red mud on mechanical properties

Properties	Effect of red mud addition
Density	Increased
Hardness	Increased
Compressive strength	Increased
Tensile strength	Decreased
Tensile modulus	Decreased
Flexural strength	Decreased
Flexural modulus	Decreased

shown in Fig. 30. The comprehensive effect of red mud on mechanical properties of developed material is shown in Table 5.

Conclusion

Experimental and analytical investigation of coir polyester red mud filled composites led to the following conclusions:

- The tensile strength of coir polyester composites improved by increasing fibre percentage initially and then decreased. Addition of filler led to slight decrease in tensile properties as load could not be transferred from fibre to resin, effectively. The best properties were found for composite containing 20 % fibre.
- The hardness and density of composite improved by addition of the red mud. Metal particles which are present in the composition of the red mud are accountable for this improvement. Hence, the prepared composite can be used for application requiring good erosive performance.
- The compressive strength of composite improved by adding the red mud. This is due to inherent high compressive property of red mud particles. Thus, the prepared composite may be used for applications requiring high compressive strength like vibration isolation base for machines.
- The buckling properties of the composites improved by increasing the percentage of fibres with maximum buckling strength which was found for 20 % fibre. Addition of red mud filler led to decrease in buckling strength by around 10 %. This may be due to inefficient bonding between fibre and resin due to the presence of filler. Thus, the prepared composite can be used for low-cost housing in rural areas.

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