Development of Sandwich Composites for Building Construction with Locally Available Materials

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Abstract

A sandwich composite comprising ferrocement skins was developed as the primary structural module for building construction with indigenous materials. The indigenous reinforcement systems selected for use in ferrocement skins were jute burlap and chicken mesh (flexible galvanized steel wire). These reinforcement systems were characterized through performance of tension tests. The tensile strength, stiffness and ductility of jute burlaps were found to compare favorably with those of chicken mesh which is a viable reinforcement for use in ferrocement. Tension tests on ferrocement sheets indicated that indigenous reinforcement ratios above a threshold level could induce multiple cracking and strain-hardening behavior, producing a desired balance of tensile strength and ductility. The tensile strength of indigenous ferrocements with jute burlap reinforcement exceeded the theoretically predicted values, which could be attributed to the favorable interactions of the burlap reinforcement with the inorganic matrix, and the strengthening effects of hydrates precipitating within the yarn voids in burlap. Experiments were conducted to determine the bond strength and the required development length of the indigenous reinforcement in cementitious matrix. Indigenous sandwich composites comprising ferrocement skins with jute burlap reinforcement and an aerated concrete core made of lime-gypsum matrix and saponin foaming agent were fabricated and subjected to flexure testing. The sandwich composite provided relatively high flexural strengths; the flexural failure modes indicated that the relatively dense aerated concrete core makes important contributions to the flexural performance of the sandwich composite.

Keywords: indigenous materials; building construction; sandwich composites; structural performance

1. Introduction

The use of locally available (indigenous) materials in construction yields economic and sustainability benefits by reducing the transportation costs and the associated energy use and carbon emissions. Building systems designed to make maximum use of indigenous materials should still meet requirements relevant to structural safety, quality of life, energy-efficiency, economy, fire resistance and durability [1, 2].

Modern buildings are generally constructed with materials such as Portland cement concrete, steel, timber, pre-fabricated gypsum panels, masonry units, polymer composites, and insulating foams [3-7]. Some indigenous materials used for building construction include adobe, rammed earth, cob, stabilized soil, stone, brick, concrete block, lime, gypsum, natural pozzolans, biomass ash, vegetable fibers (and their fabrics/ropes), bamboo and tree trunks/stems/leaves [8-17]. These indigenous construction materials are commonly used in the context of traditional building systems which provide basic shelter under regularly encountered load and environmental effects at minimum cost. Their inability to withstand extreme events (e.g., earthquakes and storms), however, has led to a significant disparity in death tolls caused by natural disasters in developing nations where the use of indigenous construction materials is common versus those in developed nations where modern building materials and systems are prevalent [18].

In this work, an approach is proposed for scalable and reconfigurable construction of sustainable, energy-efficient, and economically viable building systems using indigenous materials and locally available resources. This approach makes synergistic use of the following materials and principles:

- Use of diverse locally available plant fibers as reinforcing fabric to replace wire mesh in ferrocement [15, 19]

- Development of sandwich composites comprising exterior layers (skins) of ferrocement made with indigenous binders and fabrics, and
- Interior layer (core) of aerated concrete made with indigenous binders and indigenous foaming agents extracted from abundant plants [20, 21]

It should be noted that the reliance on less processed indigenous materials would raise the variability of material properties. Careful selection of quality control methods that can be implemented considering the constraints of indigenous construction would be important for reliable production of indigenous building materials and systems.

Fabrics made of natural (e.g., jute, sisal, kenaf) fibers are readily available in different geographic areas [22-24]. Hexagonal wire netting (chicken mesh) is also an option across the world. These indigenous reinforcement systems suit production of ferrocement, a thin-sheet reinforced cement product with a distinct balance of qualities that can be processed, using unskilled labor, into structurally efficient configurations [25]. Jute fabric (burlap) was selected for development of the indigenous building modules in this study. The fabric (burlap) as well as chicken mesh is considered in this work as indigenous reinforcement for production of ferrocement.

Ferrocement is a thin-sheet cement product where fabrics comprising relatively small-diameter wires with high specific surface area are used as reinforcement in a cementitious mortar matrix. The reinforcement volume fraction in ferrocement is relatively high when compared with that in conventional reinforced concrete [26, 27]. The high reinforcement ratio and specific surface area, and the improved bonding via mechanical anchorage of the 2D fabric (compared to 1D rebar) reinforcement induce multiple cracking in ferrocement under tensile and flexural loading. This phenomenon enables redistribution of internal forces from critically stressed areas, and enhances

the ductility and energy absorption capacity of ferrocement structures. The reinforcement volume fraction (V_r) is an important attribute of ferrocement, which depends upon (Figure 1) the number of fabric reinforcement layers (N), diameter of the fabric wires/yarns (d_w), center-to-center spacing of wires/yarns in longitudinal and transverse directions (D_L and D_T , respectively), and the total thickness of ferrocement (h) [26]:

$$V_r = \frac{N \cdot \pi \cdot d_w^2}{4h} \cdot \left(\frac{1}{D_L} + \frac{1}{D_T} \right) \quad (1)$$

<Figure 1>

In tensile loading of ferrocement (which is key to the sandwich composite performance), the cementitious matrix contributes to the tensile load-carrying capacity prior to cracking. Upon cracking, however, the tensile force is largely transferred to the reinforcing fabric. Depending on the reinforcement ratio, specific surface area and bond strength, failure could either occur at the first crack formed, or after formation of multiple cracks.

A minimum fabric reinforcement volume fraction $(V_r)_{min}$ is required for preventing brittle failure upon cracking (i.e., transfer of the composite tensile force to the reinforcing fabric at the first crack) [26]:

$$(V_r)_{min} = \frac{1}{\frac{\sigma_{ru}}{\sigma_{mu}} + 1 - n} \quad (2)$$

Where, σ_{ru} and σ_{mu} are the reinforcement and matrix tensile strengths, respectively, and n is the modular ratio of the reinforcing fabric to cementitious matrix.

With adequate area of fabric reinforcement in the direction of loading and reinforcement-to-matrix bond strength, ferrocement experiences multiple cracking. The average spacing between multiple cracks (L_{avg}) can be calculated as follows [26]:

$$L_{avg} = \frac{\sigma_{mu} \cdot Y}{\tau \cdot S_{rl}} \quad (3)$$

Where, σ_{mu} is the matrix tensile strength, Y is a constant coefficient ranging from 1 to 2 (usually taken as 1.5), τ is bond strength, and S_{rl} is the specific surface area of the reinforcing fabric in the longitudinal direction.

2. Experimental program

2.1 Materials and methods

After preliminary screening of several natural fabrics, two jute fabrics (burlaps) as well as a commonly available chicken mesh (Figure 2) were selected for use in this investigation. The chicken mesh was made of wires with 1.5 mm diameter; the hexagonal mesh openings had smallest and largest dimension of 2 and 4 mm, respectively. The ‘Jute 1’ and ‘Jute 2’ burlaps shown in Figure 2 had square openings of 1.5 and 3 mm, respectively; the corresponding yarn diameters were 1.2 and 0.9 mm, respectively. The 3-mm opening of the ‘Jute 2’ natural fabric probably makes it more suitable for use as reinforcement in ferrocement. This is because a larger opening prevents the burlap from filtering larger (sand) particles of the mortar used as matrix in ferrocement. In the ‘Jute 1’ burlap, yarns in perpendicular directions were adhered at their junctures; the ‘Jute 2’ burlap, on the other hand, comprised woven yarns (which were not adhered together).

<Figure 2>

The indigenous reinforcement systems selected for use in ferrocement were characterized by subjecting them to tension tests. The chicken mesh is not isotropic; tension tests were thus performed in two perpendicular directions. The specimen dimensions were chosen to include a minimum number of hexagonal units of chicken mesh [26]. The tension test specimens were 285

mm long and 115 mm wide, with thickness of 20 or 10 mm. For the purpose of end-gripping the jute burlap (and chicken mesh), after few trials, wooden plates were chosen, which were adhered to the fabric or mesh using the epoxy resin 862: Pro-set hardener (from Momentive Performance Materials Inc.) at 3: 1 weight ratio. The tension test procedures followed the guidelines provided in the literature [28]. Tension tests were performed on a screw-driven Instron test system with 7,000 N capacity. Tension tests were performed at a displacement rate of 0.2 mm/min; a load cell and a deflection transducer were used to collect the tensile load and deformation data. The free length of tension test specimens was 150 mm.

The mortar matrix used for preparation of ferrocement sheets comprised Type I Portland cement, silica sand with maximum particle size of 1.5 mm and water at cement: sand: water weight ratio of 1.0: 2.0: 0.5. The reinforcing fabrics used in the experimental work were ‘Jute 1’, ‘Jute 2’ and chicken mesh. Different number of reinforcement layers (1, 2 or 3) were used in this experimental investigation; higher reinforcement volume fractions were considered to induce multiple cracking.

Preparation of specimens started with placement of a layer of mortar with ~2 mm thickness inside molds (Figure 3a), followed by the addition of the first layer of reinforcement (Figures 3b, c & d for chicken mesh, ‘Jute 1’ and ‘Jute 2’ reinforcement, respectively). The sequence of adding mortar and reinforcing fabric was then repeated until the ferrocement sheet with the targeted thickness and number of reinforcement layers was produced.

<Figure 3>

The specimens were kept inside molds under wet burlap for 24 hours. They were then demolded and cured in lime-saturated water for 3 days. Subsequently, they were stored at 50% relative humidity and room temperature until the test age of 10 days.

Three replicated specimens were used for all tests, and the mean values are reported under test results.

2.2 Development of indigenous aerated concrete

Aerated concrete constitutes the lightweight core of the sandwich composite used in this investigation. Aerated concrete comprises a ‘cementitious’ matrix within which air bubbles are introduced (as replacement for aggregates in normal concrete) using a foaming agent. Aerated concrete comprises foams that were formed and stabilized in the mixing water of concrete using a surfactant (surface active agent, which lowers the surface tension of water). Saponins are natural surfactants found abundantly in various plant species. Saponin molecules are composed of a hydrophobic steroid or triterpenoid group, and one or several hydrophilic oligosaccharide chains attached to this group. Saponins are used in cosmetic, food and pharmaceutical products due to their excellent ability to stabilize emulsions and foams, and to solubilize bulky hydrophobic molecules [29]. The saponin molecule can be extracted from the residues of sisal defibering. It has been used in formulation of detergents [20]. Lime/gypsum mortar with saponin foaming agent was developed as aerated concrete. Type I Portland cement and hydrated lime were used. Saponin and calcium sulfate hemi-hydrate were purchased from Sigma Aldrich. The mix design presented in Table 1. Was identified after preliminary trials.

<Table 1>

Foam was generated in water by adding the foaming agent to half of the mixing water, followed by high-speed mixing of the solution. Mixing was continued until all water assumed the appearance of foam. The remained of mixing water was then added, and mixing was continued until a homogeneous aerated concrete was achieved.

The aerated concrete was molded into 50 mm cube specimens, which were kept under wet burlap for 3 days, and then demolded and stored at 50% relative humidity and room temperature until the test age of 7 days. The 7-day compressive strength and density of aerated concrete mixtures are presented in Table 2.

Stability of the foam structure during curing is also a key requirement in development of aerated concrete. The 7-day compressive strength of this aerated concrete formulation is comparable with those reported in the literature [30].

<Table 2>

2.3 Development of sandwich composites

A sandwich composite was prepared (Figure 4) with 20 mm skin thickness incorporating two layers of the ‘Jute 2’ burlap reinforcement, and 80 mm of aerated concrete core. This specimen had a total height of 120 mm, with length and width of 285 mm and 110 mm, respectively. The specimen was prepared by sequential casting of the lower skin, the aerated concrete core, and the upper skin inside a mold. This specimen was prepared for testing in flexure.

<Figure 4>

3. Experimental results and discussion

3.1 Characterization of indigenous reinforcement systems

Typical tensile load-deformation curve for the jute fiber yarns is presented in Figure 5. Tensile deformation initiates with a low-modulus behavior which could, at least partly, be attributed to the realignment and tightening of fibers within the yarn at the early stages of tensioning. Beyond this state, yarns behave almost linearly up to the peak load where they exhibit yielding prior to rupture. The average values of tensile strength, maximum strain at rupture and elastic modulus

(beyond the initial state of low-modulus deformation) are summarized in Table 3. Yarns are assemblies of natural fibers; they enable practical use of natural fibers at practical scales. Similar to wood, the bulk mechanical properties of yarns are a fraction of the corresponding fiber properties [31]. The tensile strengths and elastic moduli measured here are about 20% of the corresponding fiber properties. The strains at failure of jute yarns are about 4 times those of individual fibers. Since natural fiber yarns are assemblies of individual fibers, their density tends to be lower than that of their constituent fibers. The jute yarn used in this investigation had a density of about 0.9 gr/cm^3 compare to 1.4 gr/cm^3 for individual jute fibers [31].

<Figure 5>

The natural fiber yarn properties are below those provided by the steels used in ferrocement; the yield strengths of these steels, for example, are about 4 times the tensile strength of jute fiber yarns considered here. Fabrics made with natural fiber yarns, however, provide a closer yarn spacing when compared with the spacing of steel wires meshes (e.g., chicken mesh) used in ferrocement. The orientations of yarns in natural fabric are also more favorable than those in hexagonal steel wire (chicken) mesh. The higher concentration and the favorable orientation of natural fiber yarns can feasibly compensate for the lower mechanical properties of these yarns versus steel wires. Hence, natural fabrics could potentially provide bulk mechanical properties which are competitive against those of the steel wire mesh reinforcement used in ferrocement.

<Table 3>

Failure of chicken mesh involved significant realignment of wires in the hexagonal units of the mesh. With the proper end grips developed in the project, failure of burlaps occurred away from the end grips near the mid-length of specimens. Typical tensile load-deformation curves for chicken mesh, 'Jute 1' burlap and 'Jute 2' burlap are presented in Figures 6, 7 and 8,

respectively. The burlaps exhibit strain-hardening behavior marked by initial deformations at low modulus followed by a rise in modulus. As was the case with individual yarns, the initial low-modulus behavior can be attributed partly to the realignment and tightening of the fibers in yarns under tension. The peak load provided by the ‘Jute 1’ burlap is comparable to (slightly higher than) that of chicken mesh. ‘Jute 2’ with a lower solid concentration (larger yarn spacing) provides a peak load that is about one-third that of chicken mesh. The mean values of tensile strength, strain at failure and elastic modulus of the two burlaps and the chicken mesh are presented in Table 4. These results are indicative of the competitive position of the two jute burlaps versus the steel wire chicken mesh. The relatively high strain at failure of chicken mesh can be largely attributed to the significant realignment under tension of the steel wires configured into hexagonal units. It is worth mentioning that confinement in the cementitious matrix of ferrocement would reduce some of the realignments observed in tension testing of fabrics. This would influence the behavior of fabrics in ferrocement versus their behavior when tested alone (without the confinement of the cementitious matrix).

<Figure 6>

<Figure 7>

<Figure 8>

<Table 4>

3.2 Characterization of ferrocement with indigenous reinforcement

Figure 9 presents typical tensile load-deflection and stress-strain curves for the 20-mm thick ferrocement test specimens with two layers of chicken mesh reinforcement. These specimens did

not exhibit multiple cracking; the width of the first crack grew with increasing deformation on the descending branch of the load-deflection curve. The peak tensile force of the specimen with two layers of chicken mesh was about 1,900 N. This is very close to twice the ‘yield force’ of a chicken mesh specimen of similar width. It should be noted that the chicken mesh test specimen exhibited a strain-hardening behavior where force increased above the yield level with increasing deformation. This could be attributed to the realignment of wires in chicken mesh along the direction of tensile loading, which could not happen in the confined condition within matrix in ferrocement. In short, the chicken mesh reinforcement in ferrocement determined the peak tensile load-carrying capacity of ferrocement, which was equal to the yield force of chicken mesh times the number of reinforcing mesh layers.

<Figure 9>

Ferrocement specimens with 20 mm thickness and 2 layers of reinforcing fabric did not exhibit multiple cracking irrespective of the fabric type (chicken mesh, ‘Jute 1’ or ‘Jute 2’). Table 5 shows calculation of the reinforcement volume fraction for 20 mm thick ferrocement sheets with 1 and 2 layers of reinforcement. With steel mesh, the reinforcement ratios of 0.0067 and 0.0134 used here are relatively low when compared with typical ferrocement reinforcement ratios [26]. It is thus not surprising that these ferrocement specimens did not exhibit multiple cracking. In the case of natural fabric, reinforcement ratios are higher than those for chicken mesh. One should, however, consider that natural fiber (jute) yarns are relatively loose assemblies of fibers. Therefore, the yarns which constitute the fabric, unlike steel wires in chicken mesh, incorporate a high degree of porosity. The actual solid reinforcement volume fraction is thus lower than the fabric volume fraction.

<Table 5>

One can interpret the minimum reinforcement ratio introduced earlier as the threshold above which a trend towards multiple cracking would be observed. In order to evaluate the reinforcement ratios presented in Table 5, approximate calculations of the minimum reinforcement ratios $(V_r)_{\min}$ for different reinforcement systems were performed using the equation presented earlier. The results, summarized in Table 6, indicate that minimum reinforcement ratios are about three times those obtained with two layers of different fabric types in 20 mm thick ferrocement sheets. In order to reach the minimum reinforcement ratios, the thickness of ferrocement specimens was reduced to half (from 20 mm to 10 mm), and the number of layers was increased by 50% (from 2 to 3 layers). For comparison purposes, 10 mm thick specimens with 2 layers of fabric were also tested. Table 7 presents the reinforcement volume fractions in 10 mm thick ferrocement specimens with 2 and 3 layers of different reinforcing fabrics. A comparison of Tables 6 and 7 suggests that at least three layers of each reinforcing fabric should be used in the 10-mm thick ferrocement sheet in order to exceed the minimum reinforcement ratio.

<Table 6>

Figure 10 presents typical load-deflection and stress-strain curves for the 10-mm thick ferrocement specimen with three layers of ‘Jute 2’ burlap reinforcement; this specimen exhibited multiple cracking. The load-deflection curve for this specimen provided a strain-hardening behavior followed by a plateau that corresponds to development of multiple cracks after formation of the first crack. As expected, failure eventually occurs by growth of one of the cracks. Individual ‘Jute 1’ burlaps with a width similar to that of ferrocement specimens provided about 300 N peak load. While the major trend towards nonlinear behavior in Figure 10 (left) started at about 1,000 N (3 times the tensile load-carrying capacity of individual fabrics,

1 noting that the ferrocement specimen has three ‘Jute 2’ fabric layers), the strain-hardening
2 behavior of ferrocement almost doubled this load at peak. One may hypothesize that the
3 supporting role of matrix (e.g., for redistributing stresses away from critically stressed yarns and
4 regions of fabric, confinement of woven fabrics against realignment which could induce a
5 composite behavior, and filling of the pores within yarns with cement hydrates) could enhance
6 the fabric tensile strength in ferrocement versus the tensile strength of bare fabric. Although tests
7 were conducted at a young age of 7 days, there were indirect indications of filling of yarn pores
8 with cement hydrates; the yarn segments that pulled out of mortar seemed to be stiffer than the
9 as-received yarn.

10 The reinforcement volume fractions of the 10-mm thick ferrocement sheets with different
11 reinforcement systems were very close to their theoretical minimum values (see Tables 6 and 7).
12 Therefore, these ferrocement sheets may or may not exhibit multiple cracking. The ferrocement
13 sheet with three layers of chicken mesh did not experience multiple cracking. Chicken mesh was
14 found to be sensitive to the stress concentration generated at end grips; the single crack which
15 was responsible for failure of ferrocement specimens with chicken mesh reinforcement occurred
16 near the end grip. This was not the case with the ‘Jute 2’ burlap reinforcement which seemed to
17 provide a desired toughening effect and the ability to mitigate localization of damage at the
18 highly-stressed regions.

19 In the case of the ‘Jute 1’ burlap with 1.5 mm opening between yarns, considering that the sand
20 used in the mortar matrix had a maximum particle size of 1.5 mm, failure occurred by
21 delamination of the mortar coating on the outer layer of burlap while some tendencies towards
22 multiple cracking were also observed. This observation indicates that the maximum particle size
23 of sand in mortar should be smaller than the fabric opening size. Reduction of the ferrocement

sheet size to 10 mm pronounced the adverse filtering effect of the ‘Jute 1’ burlap with fine opening size against coarser sand particles. In this case, even with two ‘Jute 1’ burlaps, a brittle failure mode was observed with a peak load that was smaller than twice the tensile load-bearing capacity of a single ‘Jute 1’ burlap tested in tension.

<Table 10>

3.3 Evaluation of the sandwich composite behavior in flexure

Figure 11 presents the setup for flexure testing of the sandwich composite specimen. This ferrocement skin with two layers of ‘Jute 2’ burlap provides a peak tensile force of about 1,000 N, obtained in tension testing of a 10-mm thick ferrocement sheet with similar reinforcement condition. With 100 mm center-to-center spacing of the upper and lower skins, the ultimate flexural strength of the sandwich composite, when failure is governed by tensile rupture of the lower (tensile) skin, would be $1,000 \times 100 = 100,000$ N.mm. In a four-point flexure test over a span of 250 mm, this flexural strength translates into $6 \times 100,000 / 250 = 2,400$ N peak load.

Under increasing flexural loading, initial cracking occurred in the aerated concrete core, starting just above the lower skin, which prompted cracking of the ferrocement skin. Subsequently, with further increase in load, the tensile crack in lower skin grew, and failure occurred by full-depth cracking of the sandwich composite at the section where core cracking initiated. Failure occurred by the growth of the initial crack, without any indication of multiple cracking. Full-depth cracking of the composite specimen indicates that delamination of skins led to the loss of sandwich composite behavior, with each skin acting independently in flexure. If the sandwich composite behavior would have continued without skin delamination, ultimate failure could have induced crushing of the top skin in compression.

The flexural load-deflection behavior of this sandwich composite specimen (Figure 11) indicates that the experimentally obtained peak load (~4,400 N) is significantly higher than the theoretically predicted value of 2,400 N. This theoretical calculation considered moment to be equal to the tensile strength of skin (derived based on experimental results) times the center-to-center distance of the two skins. It neglected the contribution of the core to flexural strength, and the change in skin behavior from axial to flexural. The failure mode of this sandwich composite specimen under monotonic loading could be characterized as ductile. After removal of the failed sandwich composite specimen from the test machine, it was noted that the tension skin was fully debonded from the core. The aerated concrete core used in this sandwich composite was of relatively high density and strength; it is thus expected to raise the flexural strength of the sandwich composite. Initiation of failure by tensile cracking of the aerated concrete core implies that the tensile strain capacity of the core was not adequate, which could be attributed to the relatively high density of this aerated concrete. Delamination of the tensile skin from the core and initial cracking of the core indicate that the structural behavior of the sandwich composite would benefit from improved interfacial stress transfer and increased strain capacity of the core.

<Figure 11>

<Figure 12>

4. Conclusions

- Natural fabric (burlap) and chicken mesh are viable (indigenous) reinforcement systems for production of ferrocement, which was produced in this research with an indigenous binder developed in the project. The high reinforcement ratio and specific surface area, and the improved bonding via mechanical anchorage of the 2D fabric reinforcement induced multiple

1 cracking in ferrocement under tensile and flexural loading. This phenomenon enables
2 redistribution of force from critically stressed regions, and enhances the ductility and energy
3 absorption capacity of ferrocement structures.

- 4 • The concept of minimum reinforcement ratio for inducing ductile modes of failure and
5 multiple cracking was verified. Adequate reinforcement ratios were found to induce strain-
6 hardening type of behavior. The ultimate tensile load-bearing capacity of ferrocement was
7 found to exceed that of its constituent reinforcement. This was attributed to the stress
8 redistribution capabilities (after local fiber/yarn rupture) provided by the cementitious matrix,
9 precipitation of hydrates within yarn pores (which raises their strength), and the governing
10 role of cementitious matrix in determining the location of failure which is probably away
11 from the weakest link(s) within the reinforcing fabric. Tension test results also indicated that
12 jute burlaps can produce ferrocement sheets with structural qualities (strength, stiffness,
13 ductility) which match those offered by chicken mesh (steel fabric) reinforcement.

- 14 • Studies were conducted on indigenous sandwich composites comprising ferrocement skins
15 with jute burlap reinforcement and an aerated concrete core made of lime-gypsum matrix and
16 (natural) saponin foaming agent. The aerated concrete used here was of relatively high
17 density. Flexure tests of this sandwich composite produced failure modes which pointed at
18 the contributions of the relatively dense aerated concrete core to flexural performance.
19 Lighter cores with relatively large strain capacity as well as improved bonding of
20 ferrocement skins to the aerated concrete core would be required for realizing failure modes
21 which ensure effective use of the ferrocement skin strength and ductility towards achieving a
22 desired balance of flexural strength, ductility and toughness in lightweight sandwich
23 composites.

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Table 1. Mix designs of aerated concrete.

Binder composition	Binder	Foaming agent	Water
0.20 Lime: 0.80 Gypsum	1.0	0.002	0.6

Table 2. Compressive strength and density test results for aerated concrete.

7-Day compressive strength, MPa	Density, g/cm ³
3.65	0.91

Table 3. Mean values of the mechanical properties of jute yarns.

Tensile Strength, MPa	Strain at Failure, %	Elastic Modulus, GPa
108	7.10	3.20

Table 4. Mean values of the mechanical properties of jute burlaps and chicken mesh.

Fabric	Cross-sectional area (solid), mm ²	Tensile strength* (MPa)	Strain at failure (%)	Elastic modulus (MPa)
Chicken mesh	10.05	85.0	0.22	4000
‘Jute 1’ burlap	39.33	22.6	0.03	818
‘Jute 2’ burlap	12.46	25.1	0.09	800

* Nominal stress points at the misalignment of wires in chicken mesh with respect to the tensile loading direction

Table 5. Calculation of reinforcement ratios for 20-mm thick ferrocement sheets with 1 or 2 layers of different reinforcing fabrics.

Reinforcement Type	d_w (mm)	D_T (mm)	D_L (mm)	N	h (mm)	V_r
Chicken mesh	1.60	20.0	60.0	2.0	20.0	0.01
Chicken mesh	1.60	20.0	60.0	1.0	20.0	0.01
Jute 1	1.20	1.50	1.50	2.0	20.0	0.15
Jute 1	1.20	1.50	1.50	1.0	20.0	0.08
Jute 2	0.90	3.0	3.00	2.0	20.0	0.04
Jute 2	0.90	3.0	3.00	1.0	20.0	0.02

Table 6. Calculation of minimum reinforcement ratios for different reinforcing fabrics.

Mesh	$\sigma_{\mu v}$	$\sigma_{\rho v}$	n	$(V_r)_{min}$
Chicken mesh	2.40	85.0	10.0	0.04
Jute 1	2.40	22.6	8.0	0.42
Jute 2	2.40	25.1	3.0	0.14

Figure 1. Geometric attributes of fabric reinforcement.

Figure 2. The jute burlaps and the chicken mesh selected for use in this study, (a) chicken mesh; (b) jute 1 and (c) is jute 2

(a) Mortar layer

(b) Chicken mesh

(c) Jute 1

(d) Jute 2

Figure 3. Preparation of ferrocement specimens.

(a) Cross section

(b) Side view

Figure 4. The cross section and side view of the sandwich composite specimen

Figure 5. Typical tensile load-deformation behavior of jute fiber yarns.

Figure 6. Typical tensile load-deformation behavior of chicken mesh.

Figure 7. Typical tensile load-deformation behavior of the 'Jute 1' burlap.

Figure 8. Typical tensile load-deformation behavior of the ‘Jute 2’ burlap

Figure 9. Typical tensile load-deformation curve of ferrocement sheets with 20-mm thickness and 2 layers of chicken mesh.

Figure 10. Tensile load-deformation curve for 10-mm thick ferrocement specimen reinforced with 3 layers of 'Jute 2' burlap.

Figure 11. Sandwich composite flexure test setup.

Figure 12. Flexural load-deflection behavior of the sandwich composite.