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Case Study

Characterizing material properties of cement-stabilized rammed earth to construct sustainable insulated walls

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ABSTRACT

Use of local materials can reduce the hauling of construction materials over long distances, thus reducing the greenhouse gas emissions associated with transporting such materials. Use of locally available soils (earth) for construction of walls has been used in many parts of the world. Owing to the thermal mass of these walls and the potential to have insulation embedded in the wall section has brought this construction material/technology at the forefront in recent years. However, the mechanical properties of the rammed earth and the parameters required for design of steel reinforced walls are not fully understood. In this paper, the author presents a case study where full-scale walls were constructed using rammed earth to understand the effect of two different types of shear detailing on the structural performance of the walls. The mechanical properties of the material essential for design such as compressive strength of the material including effect of coring on the strength, pull out strength of different rebar diameters, flexural performance and out-of-plane bending on walls was studied. These results are presented in this case study.

1. Research significance

Production and transportation of many engineering construction materials requires high amounts of energy and has high levels of GHG (greenhouse gas) emissions associated with it. This can have a detrimental impact on the environment especially with the recent realization of the severity of climate change and global warming. Concrete is one of the most widely used construction materials and has CO_2 emissions associated not just with the manufacturing process of cement, but also transport of ingredients over long distances. One of the solutions to reduce the environmental impact of concrete is to use more environmentally friendly ingredients and reduce the amount of transportation required in shipping these ingredients and/or the finished material. One of the building materials, Rammed Earth (RE) also known as "Pisé de terre" or simply "Pisé" (Anderson, 2000) is the material that Ecosol Design & Construction (ED&C) Ltd and the builder members of the North American Rammed Earth Builders Association (NAREBA) have been using for construction in North Western Washington State, USA; and Southern Alberta and British Columbia, Canada. The material typically used consists of locally available sand, soil, or gravel and is stabilized using nominal quantities of cement. The author was approached was approached by the Cement Association of Canada (CAC) to undertake a research project to study mechanical properties of RE. In the recent years, RE walls construction has

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become popular. However, the structural performance of such composite walls when bent out-of-plane was not understood. This was the motivation behind performing material and structural tests on RE. This article outlines the background, methods, and procedures used to construct and study the behavior of insulated RE specimens.

2. Background

Construction using Rammed Earth (RE) that includes use of locally available soils stabilized with binders such as lime dates back many centuries. RE structures including walls have been built in numerous countries since the 1800s (Earth Materials Guidelines, 1996). Research indicates that the USA and Australia have been the pioneers in using this sustainable material in building construction (Nelson, 1976). RE structures utilize locally available materials with lower embodied energy and wasted materials than traditional method (Earth Materials Guidelines, 1996). The soil used for RE building is a widely available resource with little or no side effects associated with harvesting for use in construction. The soils used are typically subsoil, leaving topsoil readily available for agricultural uses. Often soil of reasonable quality can be found close to the location of construction, thus reducing the cost and energy for transportation. Significant cost savings can be achieved when earth (aggregates or soil) is used for construction since the material is generally inexpensive and readily available. If the amount of cement used in RE is carefully controlled, more cost savings can be achieved. Today more than 30 percent of the world's population uses earth as a building material (Anderson, 2000). In addition, RE provides good thermal mass, with inherent good heat retention in buildings and cost-savings.

Once the ingredients for RE have been selected, compression or ramming of the material can be done manually using a tamper (made of a heavy flat bottom plate connected to a long vertical handle). However, RE construction without mechanical tools can be very time consuming and labor intensive. Buildings constructed using RE reduce the need for lumber because the formwork is normally removed and reused. The forms are usually made of form-ply and end panels reinforced and secured by a system of whalers, strongbacks and integrated scaffolding. The face formwork is secured to end panels. The spacing between the end panels is determined by the wall length. The spacing between the face form-ply, which forms the faces of the wall, is determined by the wall thickness. In RE construction, one face of the wall is usually formed to the full height of the finished wall. The other face, the face of the wall at which material will be delivered, is formed up to the final height in successive 20″ to 60″ (500–1500 mm) sections. The wall length and other forming details govern the length of these panels. This step by step process allows for the placement of soil in 8″ (200 mm) lifts. It also facilitates the placement of horizontal reinforcing, additional vertical reinforcing, insulation panels, and miscellaneous electrical, plumbing and mechanical elements as well as blocks outs for architectural cavities and mechanical services. Each loose lift of soil is rammed with pneumatic tampers or hand tampers after delivery into the forms.

In a project initiated at the British Columbia Institute of Technology (BCIT), RE specimens were constructed by using very low w/c ratios and about 10% cement by mass. The specimens were constructed to simulate field conditions by field experts in this industry. Specimens were constructed to evaluate compressive strength, pull-out strength, flexural strength, and out-of-plane bending of RE.

3. Method and test set-up

The rammed earth specimens were constructed by using two locally sourced soils that were blended in a 1:1 ratio. Based on the information provided by the supplier, the fineness modulus of the soil was 3.59. The clay content was approximately 6.55% by weight. During construction of the specimens, forms with secured scaffolds were set-up. The mix contained aggregate with a maximum aggregate size of 5/8″ (14 mm) and was mixed with 10% cement by mass (batched by volume). The amount of water required in the batch was determined based on the mixer operator's experience and hence the exact amount of water to cement ratio in each batch could not be determined. Post construction, the specimens were moist cured by misting frequently for a minimum of 28 days. The details about preparation of specimen and construction is described in the subsequent sections.

3.1. Production of RE specimens

As soon as the first trial mix was prepared using a rotary drum mixer, a test cylinder was made to make sure the mix met expectations in terms of cohesiveness and workability. Fig. 1 shows the first trial specimen constructed in its fresh state. The general principle followed by the field representatives for ramming was to use a lift of 8″ (200 mm) and then compact the material to a height of approximately 6″ (150 mm).

3.2. Cylinders

Cylinders of 6″ (150 mm) diameter and 12″ (300 mm) in height were cast using 200 mm diameter PVC pipes. Cylinders were made using lifts of 6–8″ (150–200 mm), which were compacted down to about 4″ (100 mm). A rectangular block of RE was also constructed from which cylinders were cored by third-party contractors to compare the effect of coring on the compressive strength of RE. Before testing, all cylinders were weighed and dimensions measured to determine the density of RE. They were later capped using sulphur compound according to CSA 4.2.4.2 requirements. Specimens were tested using a

Fig. 1. First prototype test cylinder.

400 kip Forney machine in the concrete lab as shown in Fig. 2. The specimens were loaded at a rate of 50–80 psi/s (0.35–0.55 MPa/s). Note: 1 kip (kilo pound) = 4459 N.

3.3. Pull-out

To determine the pull-out strengths, three rebar diameters ((#3)10 M, (#5)15 M, and (#6)20 M) were used. Some were oriented vertically (along the direction of ramming) and some were oriented horizontally (perpendicular to compaction direction). The various specimens along with their designations are shown in the table below. Also, Fig. 3 illustrates the

Fig. 2. Specimen loaded in a 400 kip Forney machine.

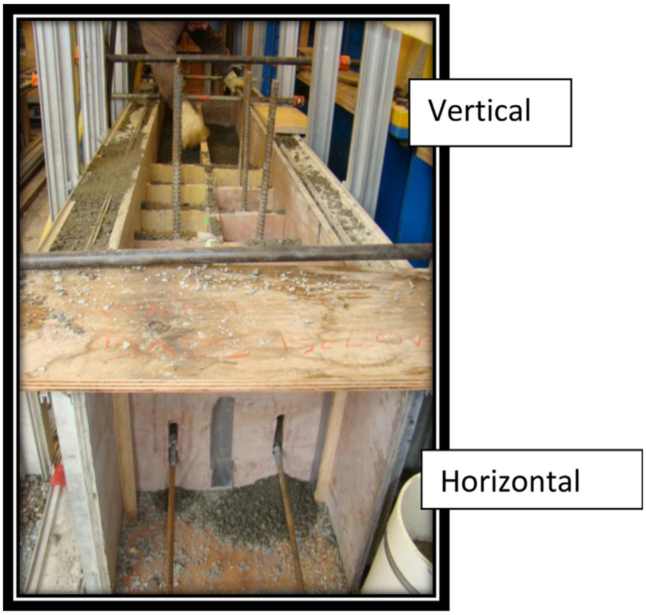

Fig. 3. Rebars layout in vertical and horizontal directions.

Table 1
Pull-out test specimens.

Specimen	Bar diameter (mm)	Embedded length (in)	Orientation
VPO 10M_A	10	11.25	Vertical
VPO 10M_B	10	11.25	Vertical
HPO 10M_A	10	16	Horizontal
HPO 10M_B	10	16	Horizontal
VPO 15M_A	15	12.125	Vertical
VPO 20M_A	20	10.5	Vertical
VPO 20M_B	20	10.125	Vertical

production of pull out samples. The actual measured embedment lengths are reported in Table 1. The specimens were tested using a Baldwin machine (set-up as shown in Fig. 4). The rate of loading was 0.56 kips/min (2.5 kN/min) approximately.

3.4. Flexural specimens (beams)

To determine the flexural capacity of RE beams, two beams of size 8″ × 10″ (200 mm × 300 mm) and 60″ (1500 mm) in length were constructed; one with 2 – #3 (2–10 M) rebars and the other with 2 – #5(2–15 M) steel rebars 2.5″ (64 mm) above the bottom edge. The two types of beams during the construction stage are shown in Fig. 5.

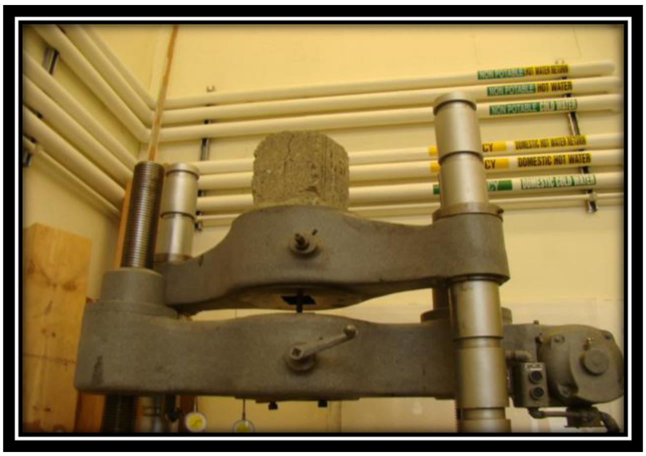

Fig. 4. Pull-out specimen loaded in a Baldwin machine.

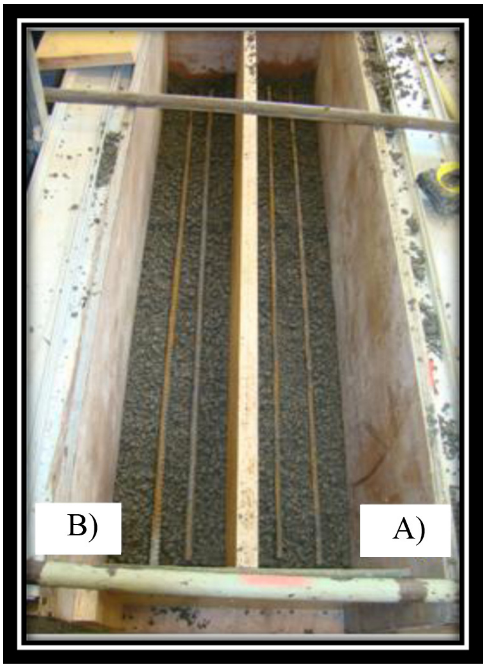

Fig. 5. (A) Beam 2 with 2 – #3(2–10 M) rebars, (B) Beam 1 with 2 – #5 (2–15 M) rebars.

The beams were loaded under a modified 3-point loading set-up as shown in Fig. 6. To avoid large bearing stress concentrations on the beams, the beams were supported on 3″ (75 mm) wide steel plates and the load was applied through a 2″ (50 mm) wide steel plate. Note, that in a typical 3-point loading test, load is applied as a line load and the specimens are also generally supported over roller supports. The modified set-up resulted in a clear span of the beam of 4′6″ (1420 mm). Beam 1 with 2 – #3 (2–15 M) rebars was tested in load control at a speed of 1 kN/min, since the ultimate load capacity of the beam was not known. This speed was increased to 0.45 kips/min (2 kN/min) after the beam reached a load of 17 kips (75 kN).

3.5. Columns (out-of-plane bending)

Two full-scale composite RE columns (representing a section of a wall) were constructed using two different types of stirrup configurations. There were four #6 (20 M) vertical rebars running the full height of the column in both specimens, but

Fig. 6. Beam setup under a modified 3-point load.


(a) (b)

Fig. 7. (a) Column with diagonal stirrups, (b) column with horizontal stirrups.

the detailing of the stirrups (#3 or 10 M) was different; either horizontally laid or diagonally placed. These configurations are shown in Fig. 7. The figure also shows how the insulation was cut to accommodate the diagonal and horizontal stirrups. Also seen in the figure is the cover distance of the rebars from the formwork. The stirrups spanned across the insulation core and were placed in conjunction with horizontal 10 M bars placed every 600 mm in the front and back of the wythes.

A special test set-up was constructed for testing the columns as shown in Fig. 8. A special steel seat was prepared to hold the columns vertically and to prevent movement horizontally. The steel seat supported the columns horizontally through a 3″ (75 mm) high plate. At the top, the column was secured using another special steel cap arrangement, which also supported the column through a 3″ (75 mm) high collar. The load was applied along the entire 2′ (600 mm) width of the column (at mid-height) using a specially constructed channel section 2″ (50 mm) wide. Both columns were tested in displacement control. Since the load or deflection capacity of the columns was not exactly known, the first column was loaded at a rate of only 0.24 in/s (6 mm/s). This rate was gradually increased in steps up to 1 mm/min as the end of the test was approached. Also, the second column with diagonal stirrup configuration was tested at rate of 0.48 in/s (12 mm/s) to begin with and the rate was

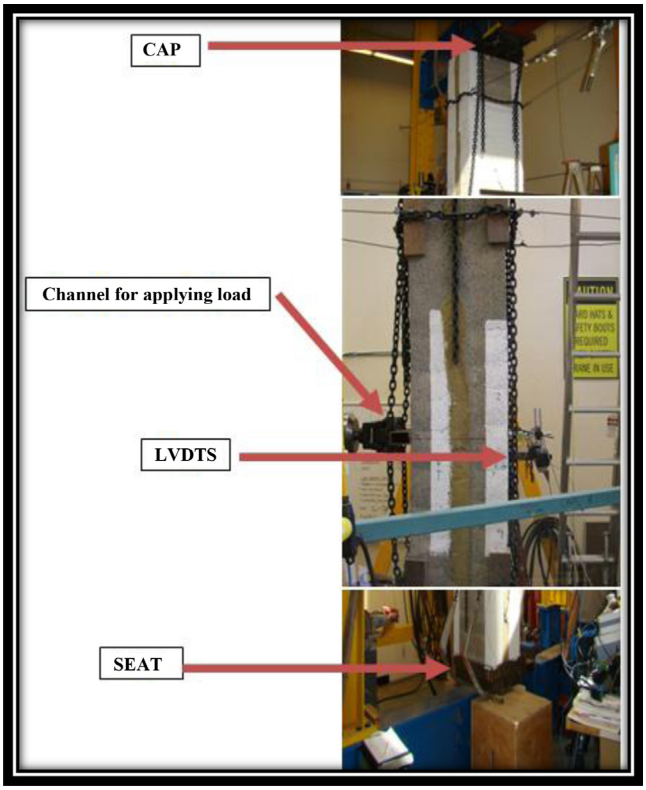

Fig. 8. Set-up to study behavior of RE column/wall.

Table 2
Compressive strength of cast and cored samples.

Age of cylinders (days)	Compressive strength in MPa (%COV)	
	Cast samples	Cored cylinders
6	12 (22%)	–
12	16 (11%)	15.5 (4%)
27	15.5 (52%)	18 (5%)
58	12.2 (55%)	–

Note: (1 MPa = 145 psi).

gradually increased as it approached to the end of the test. In addition to a few dial gauges, two LVDTs were placed along the column width to record the mid-height deflection of the columns (Fig. 8).

4. Test results and discussion

4.1. Cylinder compression testing

Cylinders were weighed and their dimensions measured before testing to calculate the density of RE. The average density of cast and cored specimens after 27 days was approximately 158 lb/ft^3 and 148 lb/ft^3 (2530 kg/m^3 and 2370 kg/m^3) respectively. Cylinders cast in molds were tested at an age of 6, 12, 27, and 58 days to determine the compressive strength in the RE cylinder specimens. The testing of samples was divided into two main groups. The first group were the cylinders cast using the 6″ (150 mm) diameter pipe. The other type were 6″ (150 mm) samples cored from a block of RE. The results of these samples were compared to that of the cast specimens to investigate the influence of any boundary effects of the molds. Table 2 summarizes results of the compression tests of cast samples. In the table, average compressive strengths are presented along with the Coefficient of Variation (COV).

In Table 2, the average compressive strength of the samples after six days was 1741 psi (12 MPa). This increased by 480 psi (4 MPa) after 12 days. The average compressive strength unexpectedly reduced after 27 and 55 days. Many factors can be attributed to this reduction and the high COV in the test results (55% at 58 days). It is hypothesized that the variability in the test results comes from the variation in: compaction effort, flatness of the top surface of cylinders and issues with capping such cylinders, RE material properties, etc. A total of six cored samples were tested each at 12 and 27 days. The average compressive strength results of these samples are compared in Table 2. The strength after 6 days increased from about 2176 psi (15 MPa) to about 2618 psi (18 MPa) after 27 days. A maximum COV of only 5% was recorded in these specimens.

The results of cast and cored samples cannot be very easily compared due to the high COV in the results of cast specimens. In any case, it seems that the average compressive strength of the cored specimens is comparable to that of the cast specimens and that the cored specimens result in slightly higher compressive strength when compared to cast specimens at 12 and 27 days.

4.2. Pull-out testing

The peak load required either for yielding, breaking, or pulling-out the rebar from the RE specimen was recorded for each specimen. This value of load was used to calculate the bond strength, based on the surface area (function of bar diameter and embedded length) of each rebar. Fig. 9 presents these bond strength values for various rebars along with the mode in which they failed. The #6 (20 M) rebars recorded the highest bond strength between 725 and 870 psi (5 and 6 MPa). High variability was observed with the #3 (10 M) rebars embedded vertically. The 10 M rebars embedded horizontally had a bond strength slightly less than 363 psi (2.5 MPa). Some pull-out specimens (including one of the #5 or 15 M) were very brittle and hence were lost during handling and could not be tested. The #5 (15 M) specimen that was tested resulted in a very low value of bond strength. Fu and Chung (1998) studied the effect of various parameters including w/c, addition of additives, surface treatment of rebar, and time of curing on bond strength. The typical bond strength observed by the authors ranged between 6 and 8 MPa As compared to these values reported by Fu and Chung, the pull-out strengths reported in Fig. 9 are lower. Treating VPO 15M_A as an outlier, all tested bars had a bond strength exceeding 1.5 MPa The 20 mm bars had a bond strength in excess of 5 MPa and both tested rebars of this diameter yielded providing adequate bond strength.

4.3. Beam testing

Load, displacement of cross-head, and deflections from two LVDTs were measured and recorded at a frequency of 10 Hz To maintain brevity, the plots are not included in this article. No initial flexural cracks were observed and the beam failed in shear at a peak load of 17.5 kips (78 kN). The deflection at the peak load was approximately 0.22 in (5.5 mm). The initial portion of this load vs. deflection plot can be used to determine the elastic modulus of the beam, which can be very useful for future analysis and design using RE. Since the approximate load capacity from the first beam was now known, the second

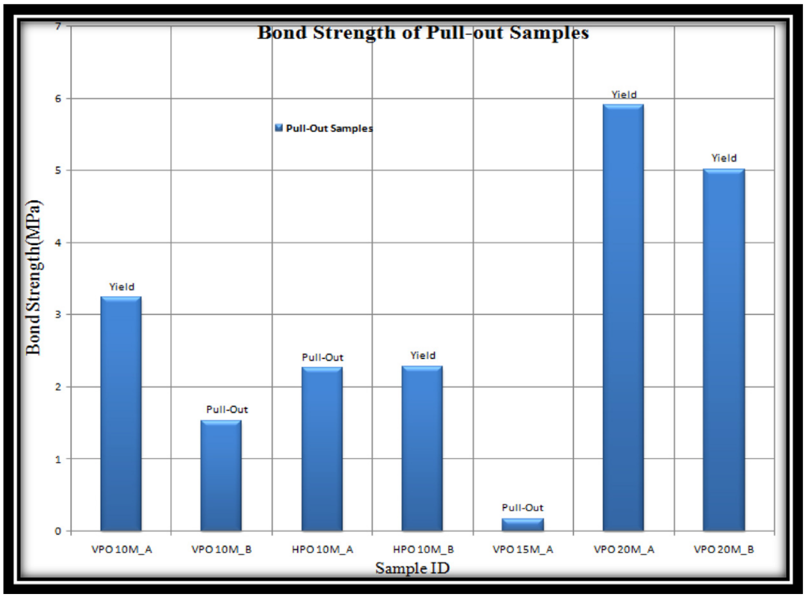

Fig. 9. Bond strength (load/surface area) for pull-out samples (1 MPa = 145 psi).

beam with two #3 (10 M) rebars was loaded at 0.45 lb/min (2 kN/min). First crack was recorded at 8.5 kips (38 kN) and ultimate failure was abrupt at 13.5 kips (60 kN).

4.4. Column testing (out-of-plane bending)

Significant time was spent in setting-up these specimens, as this required lifting of the specimens and proper placement on the test frame. The column with the horizontal stirrups was tested first. The final results (load vs. displacement) of this test are shown in Fig. 10.

As seen in Fig. 10, reasonable agreement between the LVDT readings and the cross-head (position) displacement was recorded. Due to the limit on the deflection range on the LVDTs, no data was recorded beyond about 0.6in (15 mm). The test was continued until the cross-head displacement reached a value of more than 1.2 in (30 mm). The load corresponding to this value was a little less than 13.5 kips (60 kN). Development of cracks and their propagation was also recorded during the test.

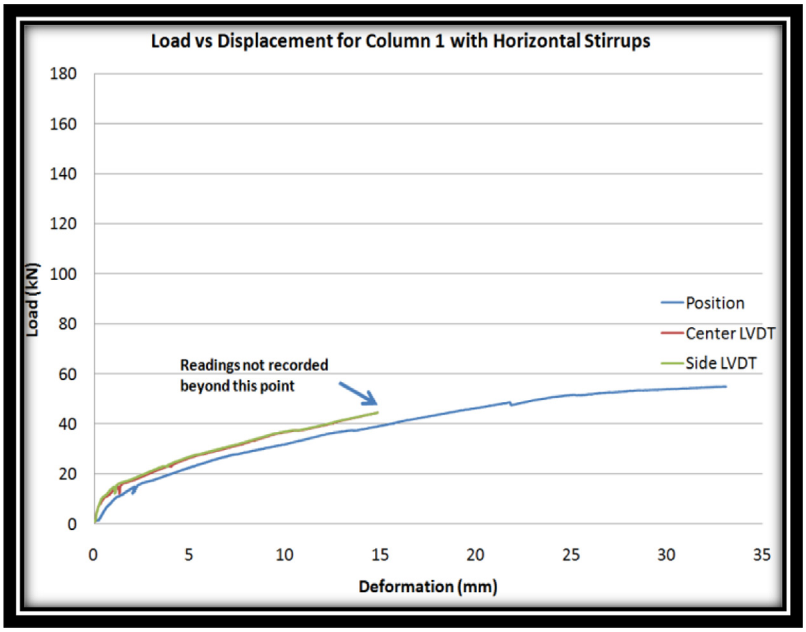

Fig. 10. Load vs. displacement for column 1 with horizontal stirrups (1 lb = 4.45 N, 1 in = 25.4 mm).

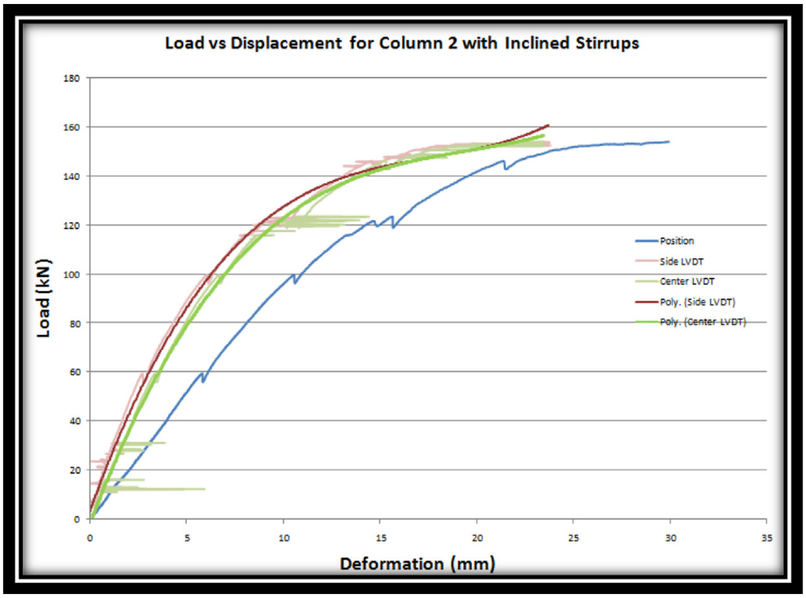

Fig. 11. Load vs. displacement for column 2 with diagonal stirrups (1 lb = 4.45 N, 1 in = 25.4 mm).

The load vs. deflection plot of the second column (with diagonal stirrups) is presented in Fig. 11. As compared to the first column, significantly higher load (~36 kips or160 kN) was recorded at a cross-head displacement of about 1.2 in (30 mm). At this point, the center LVDT and side LVDT deflected almost 1″ (25 mm). In general, the second column was much stiffer than the first one. LVDTs recorded slightly lower displacement for the same load as compared to the cross-head displacement. Since some noise was recorded in the LVDT readings, trend lines are also included in Fig. 11 for easy interpretation. As in the case of column 1, location of various cracks was recorded on the specimens.

5. Concluding remarks

This article presents the findings of a study initiated in Canada to determine the mechanical properties of rammed earth including compressive strength, bond strength, and flexural strength.

The compressive strength test results indicate that strengths in excess of 15 MPa can be easily achieved at 28 days. Cored specimens indicated a much lower standard variability. Cast specimens on the other hand can be used to measure the compressive strength, but the high variability in test results needs to be accounted for. This study also presents some interesting findings on the pull out strength of rebar embedded vertically or horizontally in RE. Rebar with 20 mm diameter embedded vertically had the highest pull out strength when compared to other specimens tested in this program. The other specimens that pulled out highlight the need for longer embedment length for rebar embedded in RE. Further research is needed in this area to confirm these findings including those of the flexural test results and develop models that can be used to design various members using RE. Two types of shear reinforcement designs were also studied by investigating the behavior of two full-scale wall panels tested in out-of-plane flexure. Further studies are underway to use the various findings to develop parameters that can be used to design structures using this innovative and sustainable material.

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