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The use of polymer stabilised earth foundations for rammed earth construction

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Abstract

This paper presents a case study as part of a Professional Doctorate research project discussing an ecological approach to housing in South Africa, where polymer stabilised earth foundations have been used to support single story rammed earth walls, in a house in South Africa. Rammed earth was chosen as a construction method for its low embodied energy and thermal mass characteristics. The subsurface strata upon which the house was built comprised of clayey, gravely, sandy soils that have resulted as a result of decomposition of granitic rocks. In order to ensure solid founding conditions the foundations were excavated to a depth of one and a half metres before the excavated material was stabilised and backfilled. The material was stabilised to 600mm below top of floor level with 2% Portland cement and above that with a 5% polymer bitumen mixture reinforced with horizontal steel reinforcing rods. This foundation avoids the use of reinforced concrete and as a result a significantly smaller carbon footprint, while fulfilling the functional requirements of supporting the building and preventing rising damp. The polymer has, as its major component is bitumen emulsion, provided a waterproof layer. Rammed earth walls of 500mm thickness were constructed on the foundation up to 4.2 meters in height and initial observations suggest that the foundations are satisfactory with no settlement or cracking detected.

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1. Introduction

This paper discusses a case study of a house, north of Johannesburg, South Africa, which was designed and built in 2014 following an ecological approach, by constructing all the walls with rammed earth. The rammed earth walls have a low embodied energy and were sourced entirely from the site upon which the house was built and stabilised with 4% lime by mass. Additional to this small quantities of natural oxides were used to colour the walls, and coupled with horizontal steel reinforcement were the only imported materials used in the walling for the house. The paper also discusses a solution to one of the disadvantages of rammed earth walls, which is that due to their width (500 mm for the case study presented) these often require large reinforced concrete footings; which reduces their ecological benefits substantially. Thus, the paper discusses the foundation design and construction and reviews other alternatives considered for rammed earth foundations and describes the salient features of the design and construction for the polymer that was used. A good review of rammed earth construction is provided by Maniatidis and Walker [1] where they emphasize the need for the foundation to be water resistant and sufficiently deep.

2. Rammed Earth Housing Context

Earth building offers a sustainable solution to housing in South Africa but has poor acceptability in the region [2]. Prior research that examined acceptability of earth building looked at adobe houses with respondents having the perception that earth buildings are subject to collapse as they are both affected by rain and are not as strong as a clay brick and cement mortar house [2]. Current research by the authors on perceptions shows promise that rammed earth has greater acceptability than other earth construction methods in southern Africa. Most housing in South Africa is built using bricks and mortar with clay fired bricks being the most common type [3]. Rammed earth construction cost has been found to compare favourably with brick and mortar construction, with formwork and labour costs the biggest component. This research is investigating both the acceptability of rammed earth as an earth construction method for affordable housing, with early positive results, as well as exploring cost efficient and suitable construction practices for the southern African region.

3. Case Study

3.1. South African House

A rammed earth house was constructed in the north of Johannesburg (Fig. 1) 25° 54' S/ 27° 56' E designed with both a low embodied energy as well as an energy efficient design. The national standards of South Africa require masonry walls to have a R value of 0,35m²K/W and as rammed earth has a value of 0,35 to 0,7m²K/W for a 300mm thick wall [1] it was deemed prudent to exceed this to achieve more than the minimum thermal performance. Walls were to reach a maximum height of 4,2 meters and at a slenderness ratio of 10 [1] would result in a wall of 420mm thickness minimum. Thus, a wall width of 500mm was chosen that exceeded both these specifications. The walls were rammed from soil from the site coloured with natural oxides and stabilised with 4% hydrated lime. The house was roofed with corrugated iron, insulated with 70mm rigid insulation below, with 800mm roof overhangs to provide both summer shading and protect the rammed earth walls.

Figure 1 North View of rammed earth house



3.2 Rammed earth foundations

The exterior walls of the project were 500mm thick and as such would require foundation walls of the same width or more as described by the rammed earth standard [4]. The options for the footings that were considered included standard concrete strip footings, cement stabilised earth footings and polymer stabilised earth footings. The carbon footprint of each system was roughly determined to derive a comparison between the systems. The concrete strip footings were deemed to have a carbon footprint with a cube of concrete having between 100 to 300 kg of CO₂ [5]. The 2% cement stabilised earth would have a carbon footprint of 40 to 80kg/m³ with cement having a carbon footprint of 250 kg/m³ [5]. The 5% polymer stabilised earth had an estimated carbon footprint of 20 to 40kg/m³ with the main components being bitumen SS60 and urea with a carbon footprint for bitumen being 102kg per tonne [6].

In comparing the different foundation options the volume of the foundations was also taken into consideration with the polymer stabilised earth being the largest, as it required deeper foundations than the reinforced concrete. The reinforcing steel content of each foundation system was deemed to be the same, so is not included in the comparison, in practice however, only horizontal reinforcing bars were used in the polymer stabilised earth foundation compared to a cage construction, that uses both horizontal and vertical steel reinforcement in reinforced concrete. It was estimated by the engineer, Hans Brink, that the polymer reinforced earth foundation required half of the steel of a reinforced concrete foundation. The results of this comparison is summarised in the following table (Table 1).

Table 1 Comparison of foundation types carbon dioxide emissions-

Foundation type	Kg CO ₂ per m ³ of material	Foundation width (mm)	Foundation depth (mm)	Foundation area (m ²)	Kg CO ₂ per linear m of foundation	% CO ₂ used	% CO ₂ saved
Concrete Strip	150	800	600	0,48	=72	100%	0%
2% Cement stabilised	40	700	1050	0,735	=29,4	41%	59%
5% Polymer	30	700	450	0,315	=9,45	13%	87%
2% Cement with 5% polymer above	70	700	1500	1,05	=38,85	54%	46%

In the final foundation design chosen a combination of 2% Cement stabilised earth with 5% Polymer Stabilised earth was used, so the final saving of CO₂ emissions was 46% over a concrete strip foundation. Bitumen production is inefficient in South Africa with a CO₂ emission of 102kg per tonne as a result of low energy costs in the past [7] compared with figures of 26-35kg per tonne the norm in Europe [6] so future work on optimising its CO₂ emission would improve the carbon footprint of this material significantly.

3.4 Foundation Design

The Walls of the rammed earth house have a maximum height of 4, 2 metres and a width of 500mm and a maximum dry density of 2027kg/m³ [8] resulting in a static load of 8513kg/m² from the walls. The roof was a lightweight steel structure at a ten-degree slope, with timber beams and purlins. The foundations used (figure 2) were a combination of cement-stabilised earth with a polymer-stabilised layer above. The foundation width was 700mm wide, the width of the Tractor-Loader-Backhoe (TLB) bucket, so very easy to excavate and wider than the rammed earth wall so providing a stable footing. The TLB excavated to a depth of 1500mm before dynamic cone penetrometer (DCP) tests were taken along the entire foundation bed to ensure that this bed was stable and no undermining was present. The material excavated was mixed with 2% cement, backfilled and compacted back in 150mm layers. DCP testing was again done to ensure that sufficient compaction was achieved. The top 450mm was mixed with the polymer and backfilled and compacted. The polymer used trades under the name of Ecobond, and comprises a plasticiser, urea, and SS60 bitumen emulsion. The percentages of stabilisation required were determined by testing samples made up of different percentages of Ecobond in a laboratory and testing their unconfined compressive strength (UCS) as well as their water resistance. After placing and compacting the foundation material DCP tests were taken at regular intervals to ensure the foundations reached sufficient strength.

The waterproofness of the Polymer stabilised earth was also a desirable quality for the floor slab, and would also result in a far lower carbon footprint and therefore the floor slab was made of two 150mm thick layers of 5% polymer stabilised earth. This was done concurrently with the foundations creating an impermeable 200mm layer

below the floor of the house. Compaction was done on the material below the floor to ensure that it had a good bearing surface before the stabilised earth was spread out and compacted to the design requirement.

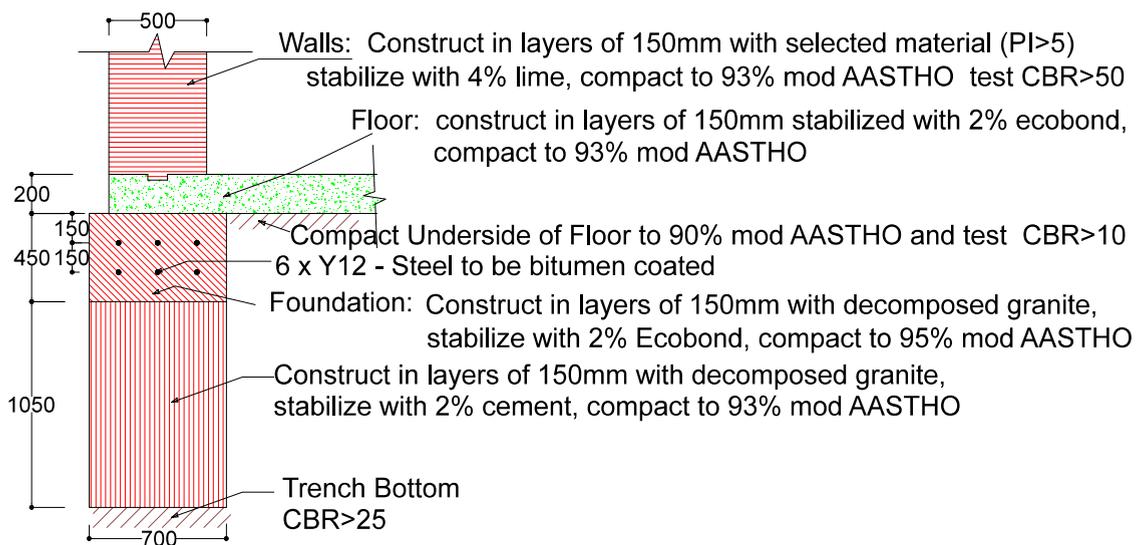
Two subsurface drains were installed at right angles to the slope, and function by diverting any subsurface water past the sides of the house thereby leading subsurface water away from the footings. One drain was installed at 300mm below the top of foundation height and a second drain was installed at 1500mm below top of foundation height. These would ensure that no water would build up against the stabilised earth foundations, and were done as a precaution to protect the earth building. A further precaution was a swale at the highest point of the property that diverted surface water around the buildings

3.5 Foundation construction method

Polymer stabilised earth is a technology that was developed for road building and as such was designed to be applied at scale with the use of extensive plant [9]. In this case study we were using the product in a house where different methods were required, to road building with far higher number and variety of under floor services, see Figure 2. This section discusses what we did and why and the difficulties we encountered.

The building practise in South Africa is to install the services in the floor slab where possible, usually the foundations, and foundation walls are built, and the subfloor compacted before the electrical and plumbing services are completed. Thereafter the floor slab is cast with the services being cast into its thickness. As we were compacting the floor simultaneously as the foundation walls, as well as the concern that the compaction would damage the services, or possibly disturb their location, it was deemed necessary to lay these underneath the stabilised floor slab before it was compacted. As the site was sloping down from south to north, an earth platform built up in 150mm compacted layers was constructed to within 200mm of the underside of the floor slab. Usual practise is to measure the location of the services off the foundation walls, to overcome this pegs were placed by an engineering surveyor at each point and a colour combination of tags used to differentiate between gas, electrical and plumbing services. A rotating laser level was used to determine floor heights on all these pegs so that the services could be set to the correct levels, critical to the drainage. These services were set 200mm below the bottom of the foundation and conduits were all equipped with draw wires so that any slight compaction at bends would not be problematic. Thereafter the earth was compacted above the services creating a hard subsurface for the polymer earth floor, (see Fig. 3 and 4). Then the trenches were excavated to 1,5 metre depth by the TLB, with some difficulty found in avoiding the services, those that crossed trenches required temporary removal. The cement-stabilised earth was mixed by hand and the polymer stabilised earth with a rotary mixer before being placed and compacted by a rammer.

Figure 2 Foundation and wall design by Hans Brink



Gauging of the cement stabilisation mixture was by standard 65 litre builders’ wheelbarrows, as per standard construction practise in the region. The mixing of the polymers was more difficult as they required greater precision and being designed for road stabilisation they were delivered in quantities designed for mass preparation in large vehicles. A method of using plastic containers cut to size, as per table 2, was devised to suit the four barrow rotary mixer, both improving efficiency and avoiding problems of incorrectly reading a measurement. Optimum moisture content (OMC) was measured before each mix to determine the required water to be added. The OMC was determined by adding a chemist’s teaspoon of water (5ml) to a can of loose soil (340ml by volume and 500g by weight) until the soil holds a ball that breaks when tapped. Each spoon of water is a per cent of the OMC.

The stabilised polymer was far more difficult to compact to level, it has the workability of sticky toffee and the presence of the services, sticking up vertically through the floor, prevented us using a large roller as recommended by the Ecobond supplier (figure 4) so a plate compactor was used. The floor was laid in 3m wide strips with gauge boards set up on both sides and a long straight edge used to level the material between them. The boards were levelled using 16mm diameter steel pegs, which provided a quick and easy method to set up a level to work from. Initial compaction was done with a rammer with the final compaction done with a plate compactor. A roller compactor had been recommended but as the distances between services were too small for it to pass, a plate compactor was used instead.

The positions of the walls were then marked out on this floor surface and a 100mm wide by 30mm deep groove cut into the floor to create a key for the rammed earth walls (figure2). Formwork was erected directly on the floor slab (figure 6), and where necessary it was chopped down to level (figure 5) and the walls were rammed directly onto this with a damp proof course deemed unnecessary. The rammed earth was reinforced with two rows of bitumen covered 12mm steel reinforcing rods with 90 degree bends below all openings as well as two rows of bitumen covered 12mm steel reinforcing rods at the top of the wall.

Table 2: Quantities of mix for 4 wheelbarrow gauge (260l) as well as water required for mix to be at Optimum Moisture Content (OMC)

Part 1	Part 2	Part 3	Part 4	1% OMC	2%OMC	3%OMC	4%OMC
1,2 l	3,2 l	153ml	5,9l	4,9l	9,9l	14,8l	19,7l

Figure 3 Completed Cement Stabilisation



Figure 4 Compacting a polymer stabilised layer



Figure 5 Polymer stabilised layer chopped down to level



Figure 6 Erecting rammed earth formwork onto stabilised base

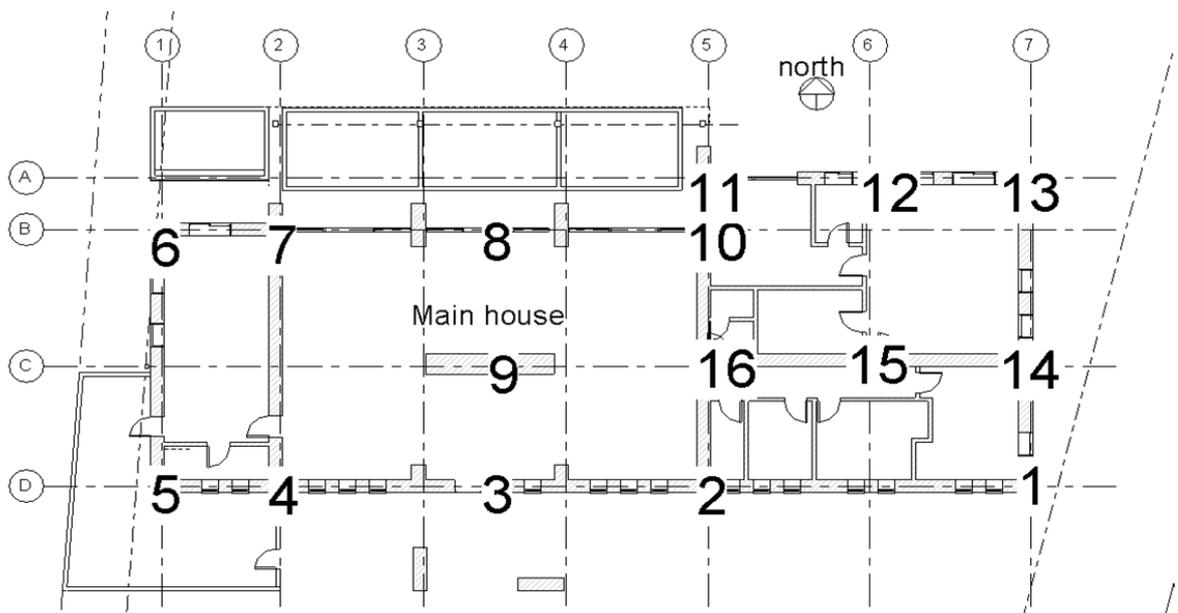


4. Site Testing and findings

Testing of the ground beneath the foundations, the cement stabilised earth and the PSE as well as the rammed earth was done with a dynamic cone penetrometer (DCP) at the positions numbered 1 to 16 (figure 7). A DCP consists of a 8kg mass dropping 575mm and knocking a 20mm diameter cone with a 60° point into the material being tested. The DCP measures the penetration rate per blow and from these results a California Bearing Ratio (CBR) is derived that gives an indication of in-situ strength. The CBR is an indirect measure of the soil strength based on its resistance to penetration. By comparing a large number of laboratory tests with field CBR values models have been developed to derive the unconfined compressive strength (UCS). A conversion that $UCS = 15 \times CBR^{0.88}$ has been derived [10] From the data collected graphs were plotted together with the CBR values (figure 8,9). Minimum CBR values had been determined by the engineer from the laboratory analysis and the loads the building was to withstand and DCP testing allowed immediate identification of any areas that were below the design specification

Heavy rains during the process of stabilisation hampered progress with a storm of 40 minutes resulting in 60mm

Figure 7 DCP test positions



of rain, the subsurface drains installed worked as designed removing most of the water. The polymer hardens and forms long chains through a dehydration process and this was significantly hampered by the surrounding wet ground (see position 7, (Figure 8)). Ecobond, the polymer used, gains strength when the polymer chains cross link and this occurs as it dries. The foundations were covered with plastic sheeting to prevent direct rain ingress, but the saturated surrounding soil had an impact on the rate the material gained strength. The ramming programme had to be adjusted to commence at the southeast corner as the northwest corner remained waterlogged for considerable time, but on drying the design strength was obtained.

These unsatisfactory results, as a result of the excessively moist surrounding soil, can be seen at position 6, which is well under design strength of a CBR of 50 (figure 9). Fortunately design strength was gained over the next 60 days, so that by the time construction of the rammed earth walls commenced the CBR value had exceeded 50. If this hardening had not occurred through the slow dehydration process, removing and replacing the PSE would have been required..

The advantage of the PSE floor was a lower carbon footprint, a waterproof layer underneath the building, and the cost saving of using material from site. A further advantage was found where services needed relocation, when it was found that it was easier to chop the PSE, as it was softer than concrete, and relocate the services with the new PSE material bonding very well with the existing material. A disadvantage of the process is that it requires compaction by layers, whereas reinforced concrete is faster and easier to place. The mixing of the PSE was complicated involving precise measurements of four different components on site, and difficulty was experienced in getting small quantities. Obtaining a flat and level surface of the PSE also proved difficult with variations in level of about 30mm throughout as a result of its sticky consistency. A cement based screed was required for the final floor finish, and this was used to achieve a satisfactory level finish. Concrete, which is the usual choice, has the advantage that it can be floated to a very smooth level finish

Figure 8: DCP plot of level below foundations 1500mm deep

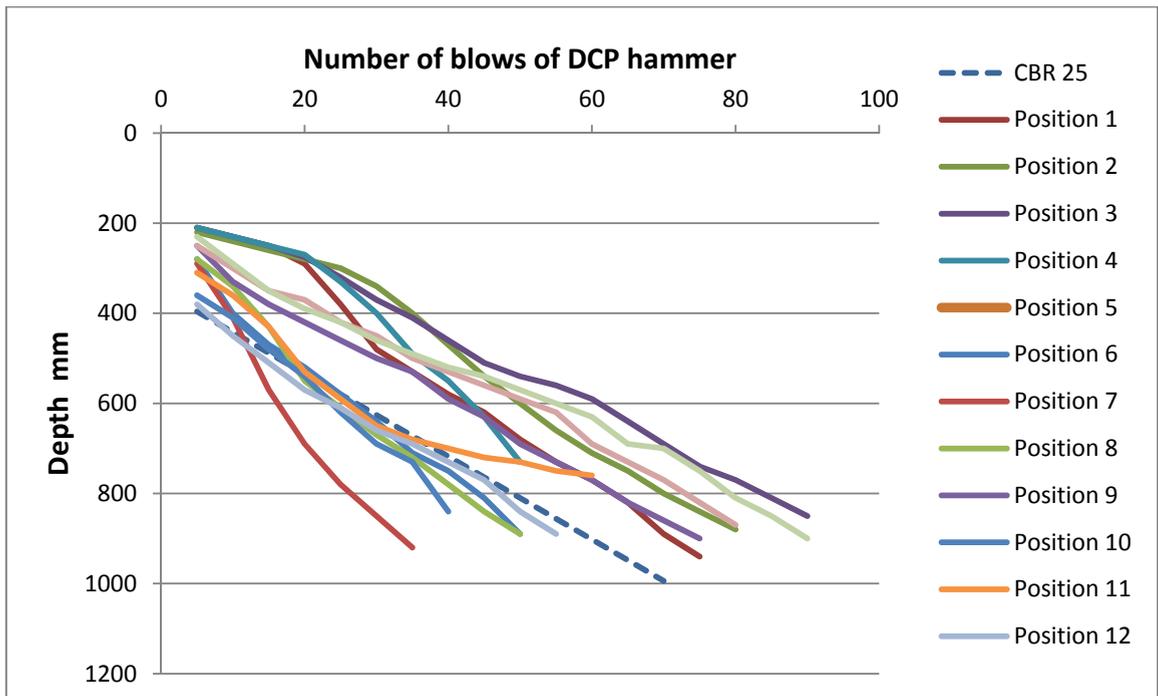


Figure 10: DCP results or rammed earth wall

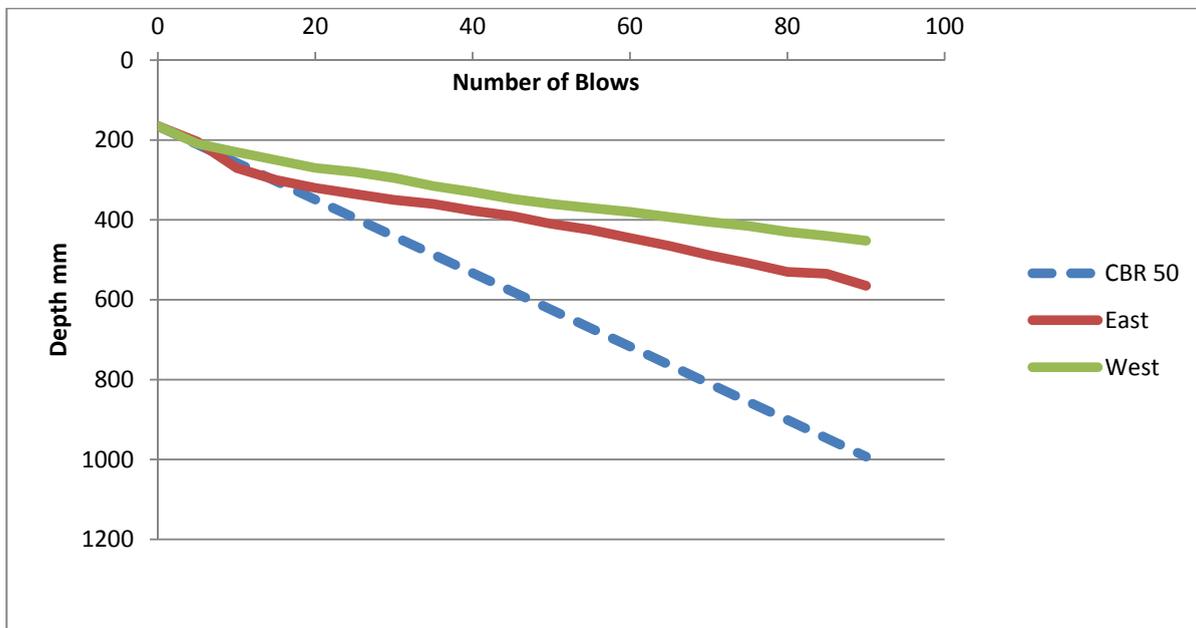


Figure 11 Shrinkage cracks



5. Discussion

Initial findings have shown that the foundation methodology is satisfactory with the rammed earth walls showing no signs of differential settlement. Ramming of the walls was done with pneumatic rammers in layers no more than 75mm thick and the DCP results were well above the design, as a result of prior layers receiving additional compaction from above, except at the very top of the wall (figure 10) where less compaction occurs. The only cracks found in the rammed earth are those below the window openings as a result of shrinkage (figure 10). These

cracks were identified early in the construction process, and were eliminated by the placement of four 12mm diameter reinforcing rods, bent 90° at the ends, below each window.

6. Conclusions

This paper was a case study of a rammed earth house that used PSE foundations for their lower CO₂ emissions, and initial investigation show that this construction method was satisfactory, cost effective and that a 46% of CO₂ emissions saving was achieved. The polymer earth foundations performed as designed with no settlement or movement shown in preliminary investigations, within the first year. The method of DCP testing adopted from road construction was an effective test method that allowed strength of the material to be easily, quickly and inexpensively tested on site.

Further investigation is necessary to optimise the construction practises, and determine the best way to accommodate services. A more suitable polymer that has higher strength, easier workability and lower cost may also be found, and alternate low CO₂ materials for foundations should be explored. The polymer requires specific soil conditions and a chart that specifies its suitability for particular earth type needs to be developed. Bitumen emulsions are also used with the addition of small quantities of cement, and their suitability should be investigated as they have lower cost. The range of earth types suitable for stabilisation needs further investigation, as well as guidelines that allow designers to choose the most appropriate solution without the need for extensive prior testing.

7. Acknowledgements

Hans Brink PrEng determined the structural requirements of the rammed earth, as well as the foundations, and was responsible for determining the testing required and the method for doing it. He offered valuable advice on the construction methodology particularly with the mixing, and levelling of the polymer earth mix. Denis Loffell PrEng for sharing freely his experience his advice on construction methodology as well as sharing freely his experience and calculations with bitumen based stabilisers.

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