AUROVILLE
EARTH INSTITUTE

Partner of the UNESCO CHAIR
earthen architecture,
building cultures and
sustainable development
CRATERRE | AE&CC | ENSAG | UGA

POURED EARTH CONCRETE (PEC) RESEARCH

BEAM REINFORCEMENT WITH STEEL AND BAMBOO

METHODOLOGY, PROTOCOL AND MAIN RESULTS

18. 01. 2014

Author: Clémentine Browne

Auroshilpam, Auroville 605 101, TN INDIA
Email: earthinstitute@earth-auroville.com
Tel: +91 (0) 413 – 262 3064 / 3330
http://www.earth-auroville.com

TABLE OF CONTENTS

1. INTRODUCTION

1.1 SCOPE AND AIM OF THE TESTS

The aim is to study the reinforcement of beams with steel and bamboo. One composition of PEC will be tested with red soil, and as well as RCC[1] and Composite beam systems. According to the results obtained with red soil, more tests will be conducted with the soil from Mangalam.

A flexural strength test will be executed on beams, in order to collect values of the maximum deflection and load for all the combinations, and to check if the reinforcement improves these characteristics. The compressive strength of PEC and PCC will be tested on cylindrical samples, with the same protocol than Testing phase 1.

Later, a pull-out test should be executed to study the bond quality between the concrete and the reinforcing material, which is one of the most important characteristics to take into account to improve the flexural strength of a beam.

1.2 HYPOTHESIS

1.2.1 Tests with red soil: comparative study of various beams

In order to get comparable data, beams of the same dimensional cross section made of different materials and with different reinforcement will be cast and tested.

1.2.1.1 Plain PEC beams (without reinforcement)

A plain PEC beam will provide us reference values of the flexural strength without reinforcement with this specific composition.

1.2.1.2 PEC beams with steel reinforcement

Flexural stress creates two different stresses in the cross-section: the lower part of the beam will endure tensile stress and the upper part compressive stress. Concrete has a low resistance to tensile stress, and steel is supposed to compensate this low resistance in extension. Then we can expect the maximum load and maximum deflection before failure increased by the reinforcement with steel, comparing with the beam without reinforcement. Single reinforcement[2] and double reinforcement[3] will be tested.

1.2.1.3 PEC beams with bamboo reinforcement

Bamboo should also improve the flexural strength of the beam, but its specific resistance to tensile stress and compression is lower than for steel. So the maximum load carried and maximum deflection is expected to be lower than with steel reinforcement but higher than for a plain beam.

1.2.1.4 PCC beams without reinforcement

This will allow comparing the flexural strength of plain PEC beams and plain PCC[4] beams. According to the results that we gathered about poured earth in terms of compressive strength, which is about half the strength of regular concrete, we can expect a better flexural strength with PCC beams than with PEC beams, but we will be able to situate the flexural strength of PEC beam taking PCC beam performance as a reference.

[1] RCC: Reinforced Cement Concrete.
[2] With the lower part of the beam reinforced.
[3] With both the upper and lower part of the beam reinforced.
[4] PCC : Plain Cement Concrete.

1.2.1.5 RCC beams with steel reinforcement

A RCC beam will be made, with the same section and reinforcement with steel than the PEC beams. As the compressive strength of PCC is higher than the one of PEC concrete, and as the bond between steel and regular concrete is expected to be better, the flexural strength of the RCC beam is expected be higher than the one of a PEC beam.

1.2.1.6 RCC beams with bamboo reinforcement

Another reinforced cement concrete beam will be made with the same sections, but reinforced with bamboo. It will allow us to compare the flexural strength and maximum deflection with the values obtained with reinforcement with steel.

1.2.1.7 Composite beams with steel reinforcement

A composite beam will be cast with a similar reinforcing network with steel and the same section as for the previous samples. It is a composite beam system of U-shaped CSEB into which reinforced concrete is cast. Single and double height composite beams will be tested.

1.2.2 Tests with soil from Mangalam

Beam samples done with the soil from Mangalam will follow the same reinforcement details for the beams, both for steel and bamboo as for the red soil. These tests will be done later, after getting results about the reinforcement with red soil.

2. SAMPLE PREPARATION

2.1 CHOICE OF THE MATERIALS

2.1.1 Bamboo [1, 2]

The bamboo culms should be carefully chosen because their characteristics will directly impact the bond between concrete and bamboo.

1. The ideal is to select at least three or four-year old bamboo. They are recognisable for their pronounced brown colour. Past this age, the strength declines.
2. The longest of large diameter culms should be selected.
3. Unseasoned or green culms should not be selected.
4. It is better to cut them before they get high moisture content in the fibres, which means cutting them preferably before the monsoon.

About one-meter culms plants should be picked up, taking into account that nodes have a strong influence on the characteristics of the culm, so the culms used for the tests should have approximately the same number of nodes. They are supposed to improve the resistance and wedge the mix. About 20mm width is ideal.

After cutting the culms, they should season and dry during at least 3 or 4 weeks before being used. The drying process is really important. It can also improve the adhesiveness of the surface of the bamboo.

The bamboo culm should then be split into splints approximately ¾ inch wide for the larger culms. When the whole culm is less than ¾ inch in diameter it can be used without splitting. To split the culm, the base has to be separated with a sharp knife and then cut along the length by pulling a dulled blade through the culm.

To make the stirrups with bamboo, we can bend them permanently if heating it while applying the pressure. Hooks and C-shaped stirrups can be made this way.

2.1.2 Coating

It is important to apply a coating on bamboo to improve the bond between the reinforcement network and the concrete. It is, indeed, the main limit of reinforcement, because the failures occur first because of the weakness of this bond. Bamboo is known to absorb water when the concrete is cast and cured, and therefore swells, provoking cracks in the concrete, and creating gaps between the reinforcement and the concrete while shrinking. [2]

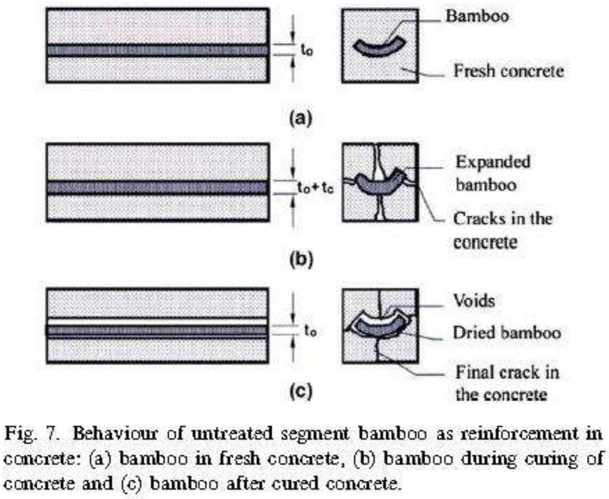


Figure 2-1: Behaviour of untreated segment bamboo as reinforcement in concrete [2]

Therefore, it needs to be waterproofed. In order to determine the most adapted product to apply as a coating for the bamboo, which means the coating that has the best bond (adhesion) with bamboo, some preliminary tests have to be done on different products. For that purpose, there are three common tests: the scrape adhesion test, the pull-off test and the cross-cut test. The scrape adhesion test consists in pressing the surface to test under a rounded stylus loaded with increasing amounts of weights. But it is mainly applicable to flat panels. The pull-off test requires some portable adhesion tests that we do not have: perpendicular dollies are tight to the surface and the force applied to them gradually increase, until the coating is detached. Finally, the third test which is called cross-cut test (or cross-hatch) is rather simple and applicable to our case, even if bamboo is not a flat surface. Therefore, we will perform this test (see section 3.1) and the coating that will show the best adhesion with bamboo will be selected for the tests.

The products tested will be solid tar, liquid tar and epoxy resin.[5]

Only a thin layer of coating should be applied on the bamboo, because a thick coating would lubricate the surface and weaken the bond between the concrete and bamboo. [4]

2.2 TESTS WITH RED SOIL: BEAM SAMPLE PREPARATION AND CASTING

Three beams of each type are poured, in order to get accurate results with the flexural strength test.

Note: For every PEC and PCC mix, a slump test is done (see section 3.2) to evaluate the workability.

[5] Coal tar has been tested among other products for coating on bamboo and has shown a really good quality of bond with bamboo [3]. Araldite also showed really good results according to this study but would be too expansive to use as a coating for the entire reinforcing network.

2.2.1 Mix ratio for PEC beams

The mix ratio that is used for the PEC concrete beams corresponds to the composition that showed the best results in Testing phase 1, in terms of dry and wet compressive strength, shrinkage and water absorption. Nevertheless, we have to consider that too big gravels would not allow a good distribution of matter inside the beam, due to the presence of the bamboo or steel network inside the beam. Then, in the selected composition, the 1" gravels are replaced by ½" gravels.

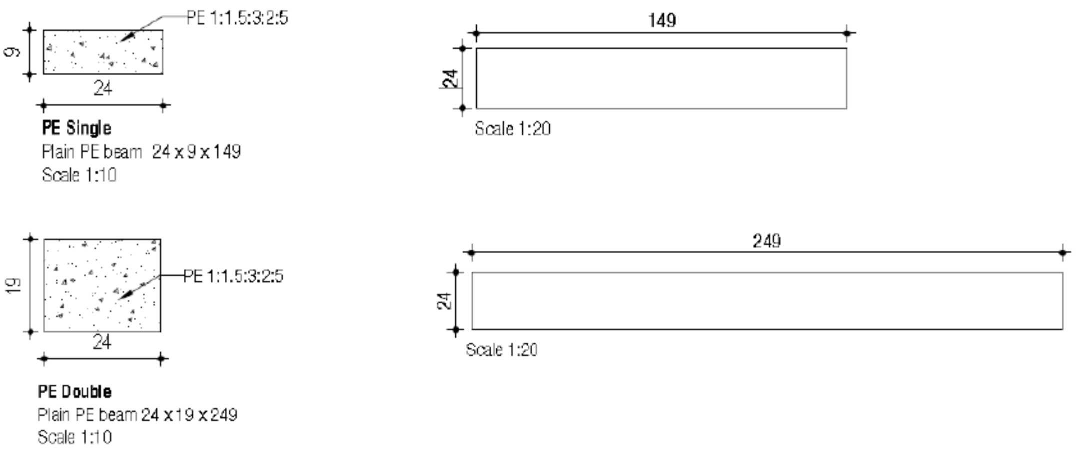
Component	*Cement*	*Soil*	*Sand*	*¼" gravel*	*½" gravel*
By parts	1	1.5	3	2	5
% of the volume	7.5% (by weight)	13%	26%	17%	43%

Table 2-1: Desired composition for the PE beams with red soil

Six cylinders are poured with this composition, in the 200 x 105mm cylindrical moulds that we have. As it is slightly different from the mixed used for 1CyR3 in Testing phase 1 (see ..\1 Testing phase 1 - mix ratios\01 Design of cylinders and results.xlsx) we will test again three cylinders in wet compression and three in dry compression.

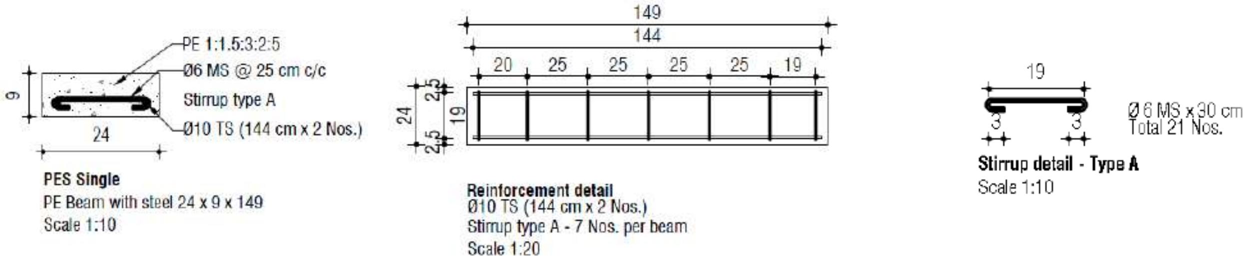
2.2.2 Plain PEC beam (without reinforcement)

The two sections tested are 24x9x149cm and 24x19x249cm[6].



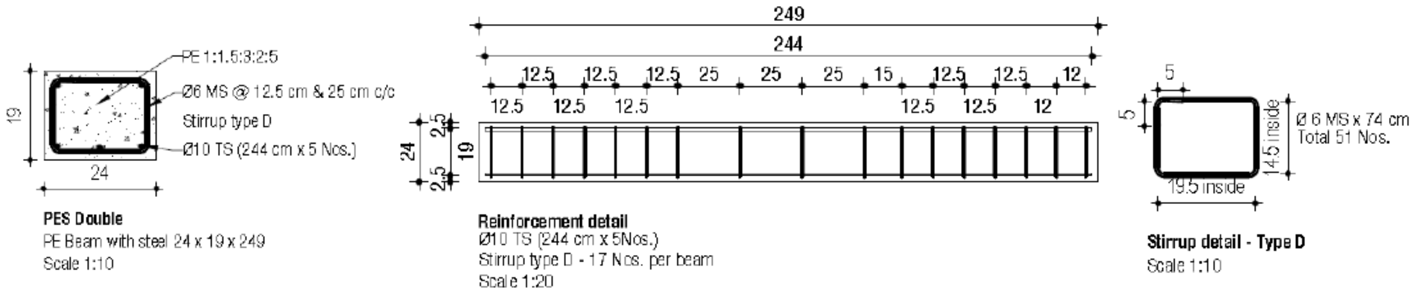
2.2.3 PEC beam reinforced with steel

The same beams as in 2.2.2 are made, with the same composition for the earth concrete, adding a single reinforcement with steel for the 24x9x149cm beam and a double reinforcement with steel for the 24x19x249cm beam.



-

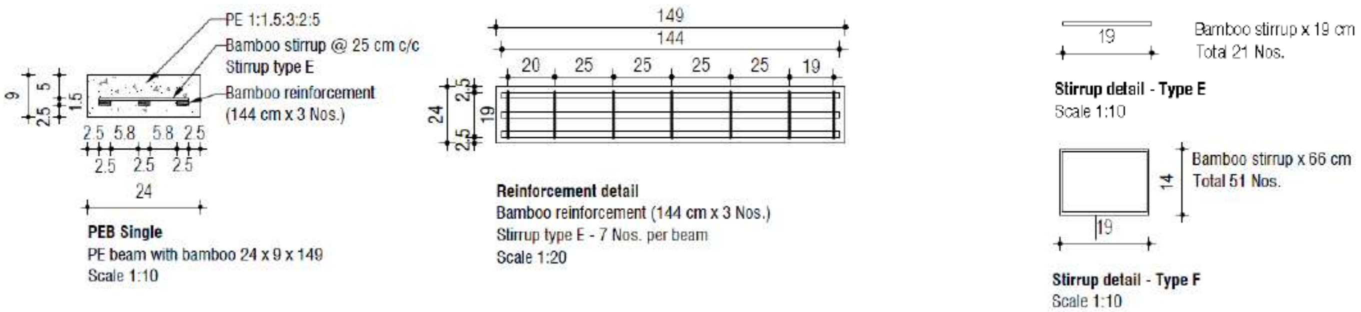
[6] These lengths of 149 and 249cm correspond to the lengths of simple height and double height composite beams.

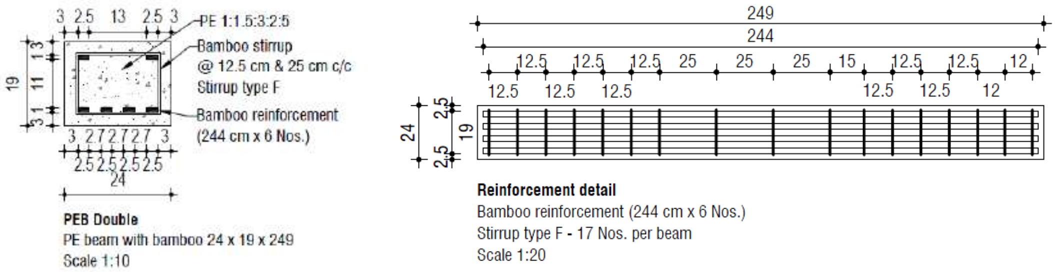


2.2.4 PEC beams reinforced with bamboo

Again, the same beams as in 2.2.2 are made, adding single height reinforcement for the 24x9x149cm beam and a double height reinforcement for the 24 x 19 x 249 cm beam, with bamboo.

After cutting the bamboo into splints, the dimensions should be measured in 5 points along the length (to get an average dimension of the cross-section of the culm).
Reinforcement should not be placed less than 1" from the face of the concrete surface. When using whole bamboo culms, the top and bottom of the stems should be alternated in every row and the nodes or collars, should be staggered. This will insure a fairly uniform cross section of the bamboo throughout the length of the member, and the wedging effect obtained at the nodes will materially increase the bond between concrete and bamboo. The clear spacing between bamboo rods or splints should not be less than the maximum size aggregate plus 1/4 inch. Reinforcement should be evenly spaced and lashed together on short sticks placed at right angles to the main reinforcement. [1] The stirrups will be made with split sections of bamboo, which can be bent permanently if heated. A horizontal stick will tie the culms for the 24x9x149cm beam and a square-shaped stirrup will tie them for the 24 x 19 x 249 cm beam.
Bamboo must be securely tied down before placing the concrete. It should be fixed at regular intervals of 3 to 4 feet to prevent it from floating up in the concrete during placement and vibration.





2.3 TESTS WITH PCC: BEAM SAMPLE PREPARATION AND CASTING

2.3.1 Mix ratio for PCC

A classical composition of <PCC 1: 2: 4> is used for the concrete.

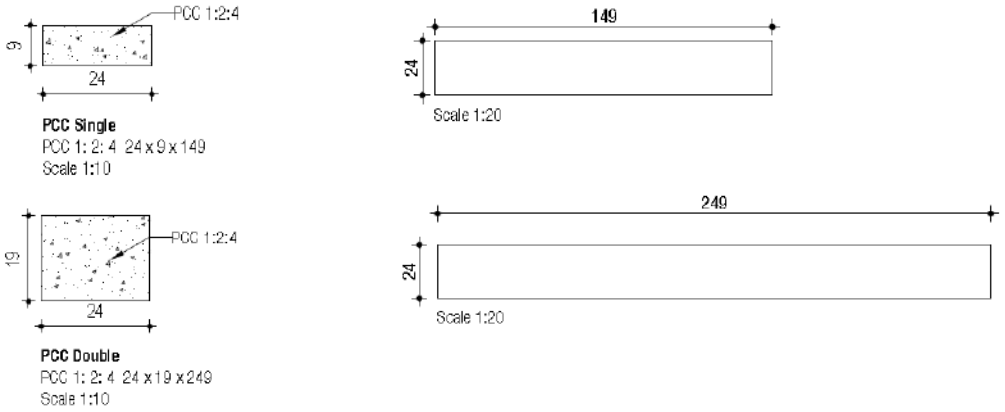
Cement	*Sand*	*½" gravel*
1	2	4

Table 2-2: Desired composition for the RCC beams with red soil

Again, six cylinders are poured with this composition to get the dry and wet compressive strength of this mix.

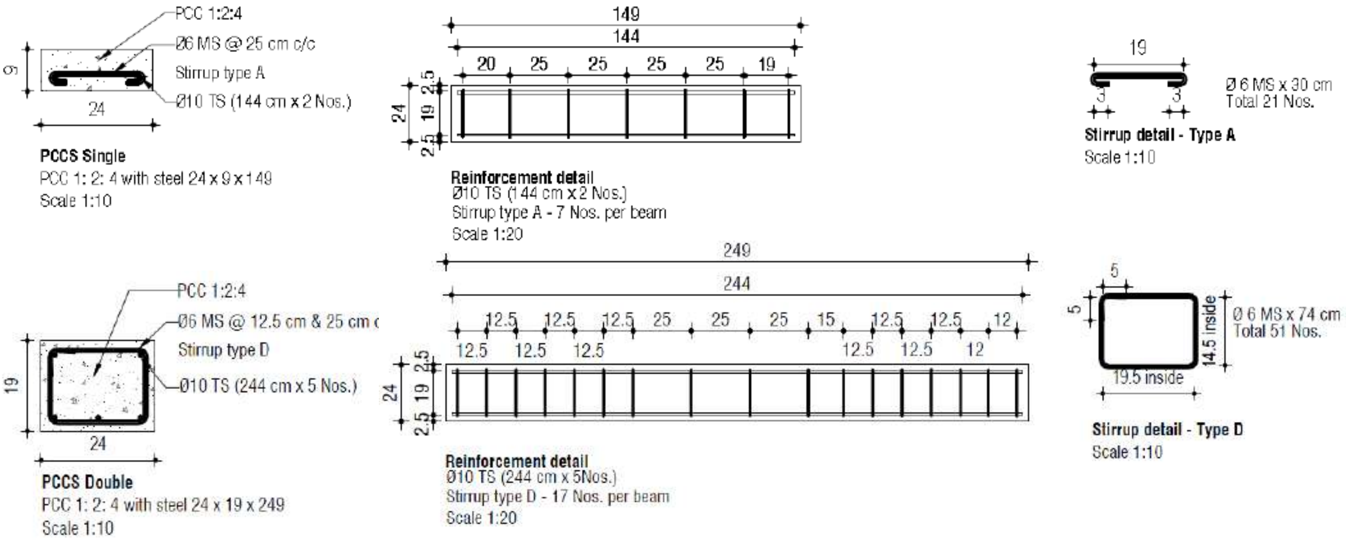
2.3.2 Plain PCC beam

For each section, three plain PCC beam are poured in order to compare the flexural strength with the one of a plain PEC beam.



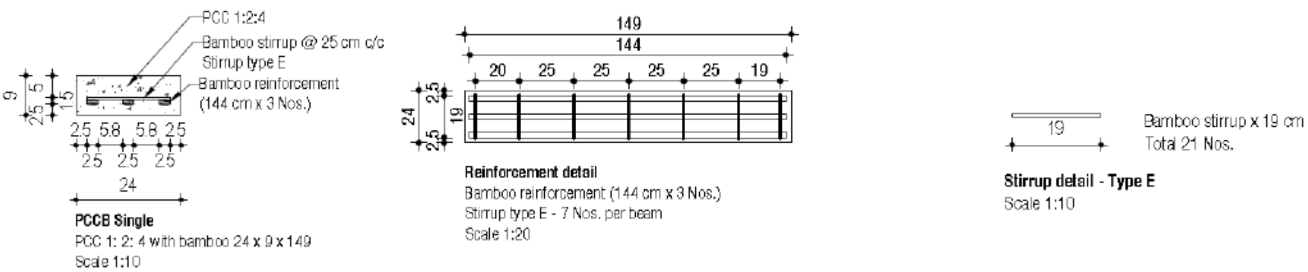
2.3.3 RCC beam reinforced with steel

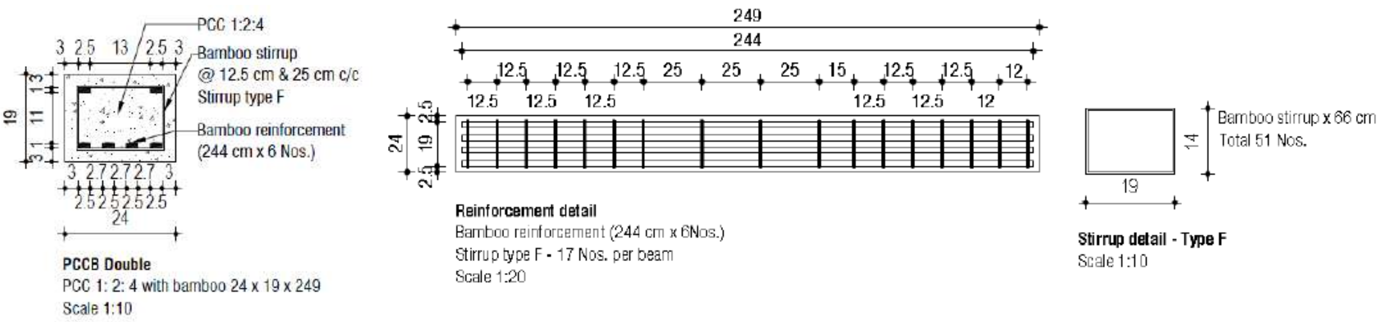
Again, three beams of each section are cast, according to AVEI specifications (see Work Specifications for AVEI earth construction techniques, page.51) to make RCC beams.



2.3.4 RCC beam reinforced with bamboo

The same beams than in 2.2.4 are poured, replacing the poured earth concrete with the same <PCC 1: 2: 4> as specified in 2.3.1.

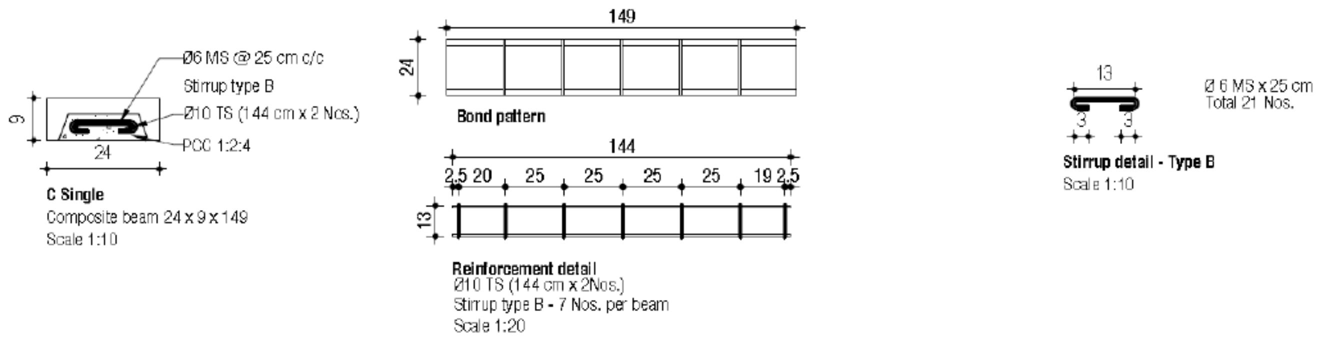


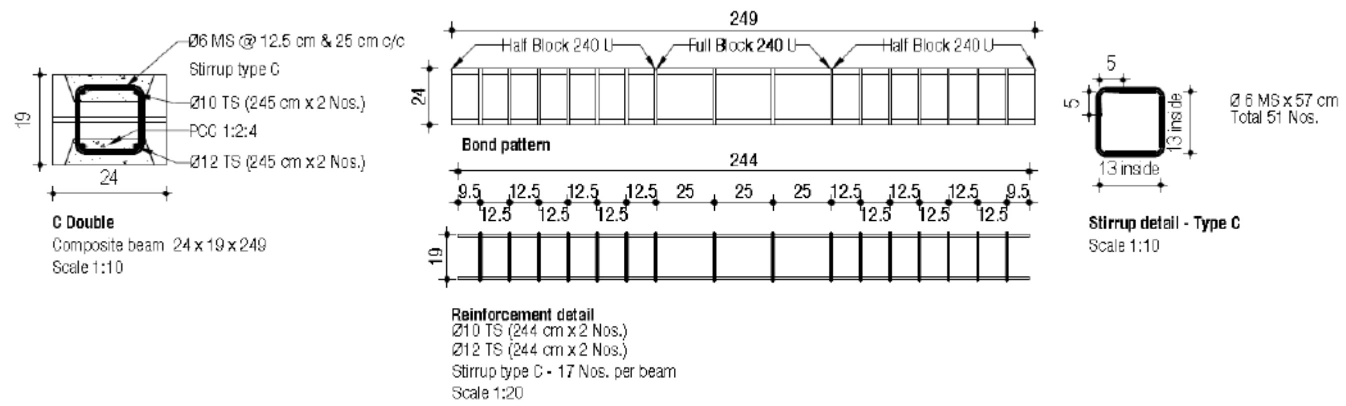


2.4 TESTS WITH COMPOSITE BEAMS

Again, three composite earth beams for each section are made. One section corresponds to single height beam, with one U-block and a single steel reinforcement, and the other section is a double height beam with two U-blocks and a double steel reinforcement.

According to the specifications by AVEI to make a composite beam (see Work Specifications p. 35), the concrete cast in the U-shaped block is <PCC 1: 2: 4> and the mortar is a cement sand mortar <CSM 1: 3> with a thickness of 1cm.





2.5 TESTS WITH MANGALAM SOIL

The samples have the same composition as for the red soil. Three samples of each beam type are cast:

- Plain PEC beams (without reinforcement);
- PEC beams with steel reinforcement;
- PEC beams with bamboo reinforcement.

The frame is removed 24 hours after pouring the concrete. Then, the samples are cured several times daily for 28 days. Samples must not dry for 4 weeks. For the double height composite beams, after one side has been cast, the beam should not be moved for 3 weeks before turning it and casting the other side.

3. TESTING PROTOCOL

3.1 CROSS-CUT TEST [6]

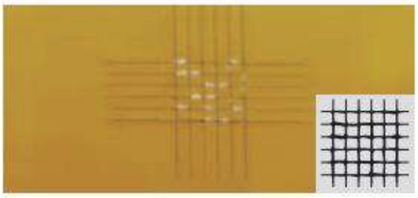
This protocol is inspired by ASTM D3002 – Evaluation of Coatings applied to plastics, ASTM D3359 – Measuring adhesion by tape test and ISO 2409 – Paints and Varnishes Cross-cut test. We cannot meet all the requirements of these standards, because of some tools we do not have (the special blade required and the illuminated magnifier).

A surface as flat and straight as possible should be found on the culm to perform the test, because it is normally applied to flat surfaces. A thin and uniform layer of coating has to be applied on a consequent surface of the bamboo culm and then let to dry. As we do not have at our disposal the special blade required for this test, which is a kind of scraper with 7 tines, we made our own tool with nails sank and glued into the holes of an electronic card.

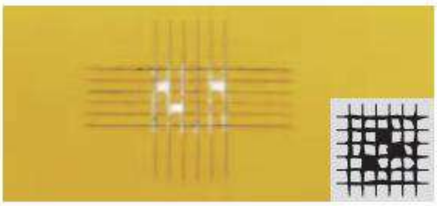
1. With the blade, a lattice pattern is made in the coating, cutting to the substrate. For coatings of thickness of 50um or less, a fine blade (1.0 mm spacing) should be used; for thickness between 50 and 125um, a medium (1.5mm spacing) or coarse (2.0mm spacing) blade should be used. The pressure should be just as much as needed to reach the substrate. The second cut should make a grid, crossing the first cut at 90 degrees.
2. The cut is then taped over, firmly rubbed with a pencil eraser to ensure a good contact. Then, to remove it, it should be pulled parallel to the substrate length.
3. The grid area can be observed and the quality of adhesion characterized in function of its visual appearance:

■ ISO Class.: 0 / ASTM Class.: 5 B
The edges of the cuts are completely smooth; none of the squares of the lattice is detached.

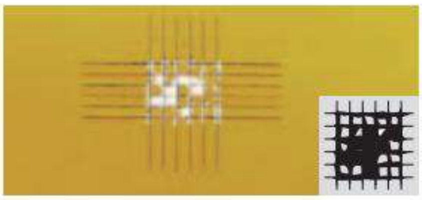
■ ISO Class.: 1 / ASTM Class.: 4 B
Detachment of small flakes of the coating at the intersections of the cuts. A cross-cut area not significantly greater than 5 % is affected.



■ ISO Class.: 2 / ASTM Class.: 3 B
The coating has flaked along the edges and/or at the intersections of the cuts. A cross-cut area significantly greater than 5 %, but not significantly greater than 15 %, is affected.



■ ISO Class.: 3 / ASTM Class.: 2 B
The coating has flaked along the edges of the cuts partly or wholly in large ribbons, and/or it has flaked partly or wholly on different parts of the squares. A cross-cut area significantly greater than 15 %, but not significantly greater than 35 %, is affected.



■ ISO Class.: 4 / ASTM Class.: 1 B
The coating has flaked along the edges of the cuts in large ribbons and/or some squares have detached partly or wholly. A cross-cut area significantly greater than 35 %, but not significantly greater than 65 %, is affected.

■ ISO Class.: 5 / ASTM Class.: 0 B
Any degree of flaking that cannot even be classified by classification 4.

Figure 3-1: Characterization of the adhesion according to ISO and ASTM standards

Then the coating that showed the best adhesion to the bamboo is selected.

3.2 SLUMP TEST

Before pouring the concrete into the moulds, a slump test is done to evaluate the workability of the concrete. This protocol corresponds to the European standard NFP 18-451. In order to perform this test, an Abrams' cone is used. It is a cone of 30cm height, 10cm superior diameter and 20cm inferior diameter, which makes a volume of 5.5 litres.

1. The cone is oiled on the interior surface to avoid friction. Then the admixture is poured in it in three equal layers.
2. A 1,6cm diameter rod is then be used to tamp down the admixture 25 times per layer in order to allow air bubbles to escape and to compact roughly the admixture. The top of the cone is finally levelled with the rod.
3. Then the cone is removed slowly and put beside the admixture to measure the slump easily.

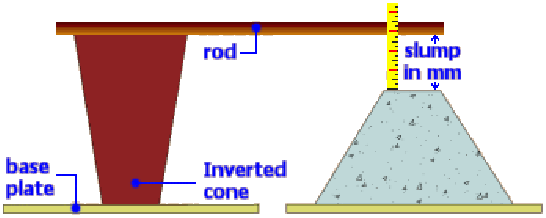


Figure 3-2: Slump test

In fact, the amount of water added should be as low as workability will allow. [7] An excess of water would cause the swelling of the bamboo, which provokes cracks in the concrete and then gaps when the bamboo shrinks (see section 2.1.2).

3.3 FLEXURAL STRENGTH

After 4 weeks of curing and about 1 week drying (more or less 2 days), the beams can be tested in flexion. A uniform load along the beam is created by loading bags of cement filled with quarry dust. There are two supporting points, 125mm away from each end of the beam. Bags are added successively, starting from the centre, to measure the maximum load before failure.
A dial gauge is placed at midspan to measure the deflection and determine the maximum deflection before failure.

4. MAIN RESULTS

4.1 TESTS FOR COATING

Several trials were done to find a good solution for coating the bamboo. First, a cross-cut test was performed with liquid tar, solid tar and epoxy resin:

Figure 4-1: Grids for cross-cut test. From left to right: liquid tar, solid tar, epoxy resin

Figure 4-2: Touching liquid tar 10 days after applying it

Liquid tar is obviously non convenient because it does not harden on bamboo.

Several weeks after applying it, it was still sticky. The cross-cut test did not work anyway, for several reasons: the grid was made with a homemade tool instead of an appropriate blade that was not really efficient, due to the fact that the surface of bamboo is not flat.

No real conclusions can be drawn; the grid is slightly more damaged after removing the tape on the epoxy sample but it is not very significant. The criteria that made us chose epoxy is that solid tar sets too fast and is difficult to apply in a thin and uniform layer.

Then other tests had to be performed in order to choose the right coating.

The next step was a trial to improve the roughness of the surface of the bamboo, and therefore the adhesion with concrete. As it was not hardening well, liquid tar has been removed from the tests at this point. We tried to stick two types of sand to the coating: river sand and coarse sand. We found out that river sand is too thin to stick well, and makes the surface still too smooth. coarse sand hardly sticks and we notice that when we pull it off, the resin is also removed (see Figure 4-3).

Apparently, it could be because of a sort of wax that covered the surface of the bamboo.

Figure 4-3: Solid tar with river sand / Solid tar with coarse sand; Epoxy resin with river sand / Epoxy resin with coarse sand

Figure 4-4: Trial with coarse sand and resin

Then, in the next series of test, this wax was removed by brushing the surface with a steel brush. The same tool than for making the grid of the cross-cut test was used to stripe the surface of the bamboo, to induce a better adhesion with the coating. We found out that the bigger particles of coarse sand could not stick to the surface, and that the finest ones prevented the others from sticking. Particles should be big enough to create a roughness that will reinforce the bond with concrete. Coarse sand was then sieved for the next tests, keeping the particles between 1 and 2 mm.

Figure 4-5: Striped surface of the bamboo / Tool used for making the grids and the stripes / Applying sieved coarse sand on the striped surface with epoxy resin

Another noticeable fact was that the sand was slowing down the setting of the resin. Then it takes several days to harden and the coating of the bamboos has to be prepared in advance.
The procedure that was finally chosen to coat the bamboos is:

- Scrape the surface of the culm with a steel brush.
- Stripe it with the nailed-tool
- Apply the resin and right after put the structure in the sand, sieved between 1 and 2 mm, pressuring it.

Before casting the beam, the bamboo reinforcement is brushed to remove the sand that is not stuck in the hardened resin.

4.2 BAMBOO REINFORCEMENT MANUFACTURING

After this preliminary treatment, each element of the reinforcement is waterproofed and a layer of sand is applied. A few days of drying are necessary before the reinforcement is created.

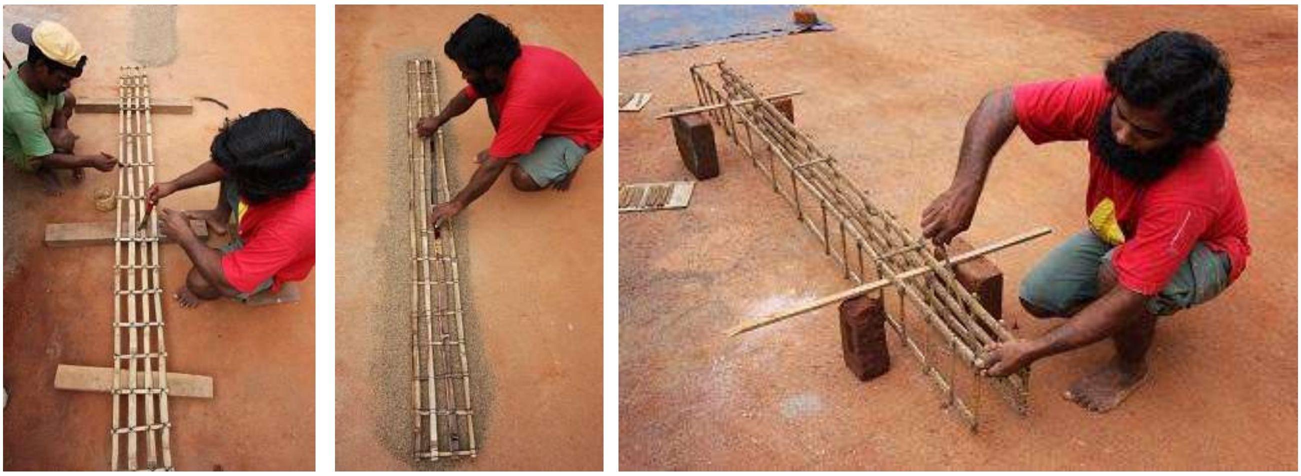


Figure 4-6 (from left to right): Applying resin, applying sieve sand, fixing stirrups

Unfortunately, we have not yet experimented with an alternative solution to wire to bind the different elements of the reinforcement together. The stirrups are square in shape and are made up of four pieces of bamboo that are tied together. Afterwards we will try to heat the bamboo to form 90° angles and thus make the stirrup of a room, minimizing the steel required. It is also possible to bind them with fibres, which can be tried in future tests.
The steel reinforcements are made as for a standard beam.

4.3 BEAM CASTING

The formwork is prepared directly on the ground, which is oiled. In the case of a PE beam, a thin plastic sheet is placed on the floor to prevent the beams from adhering too much to the ground. The mixture is carried out as for the first samples: first the dry mixture without gravel, then the gravel is added and finally the water is measured with a slump test. The test values for the workability of concrete suitable for beams are between 18 and 23 mm. A first layer of concrete is then poured before reinforcement.

Figure 4-7: Formwork preparation, concrete mixing, slump test, pouring of the first layer

The reinforcement is then placed in the formwork. These tests have made it possible to realize that it is very difficult to respect the necessary coverage on each side because the rods used for the reinforcement are curved.

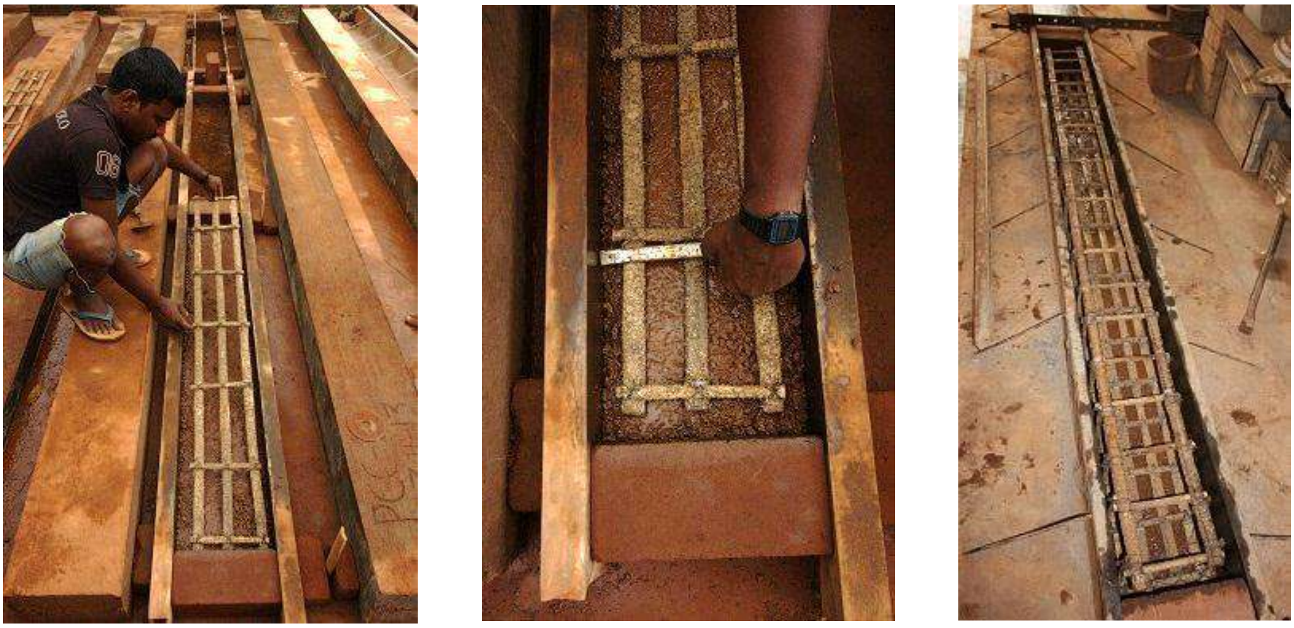


Figure 4-8: Placement of the single-height reinforcement in a 24 x9 x 149 cm formwork, measurement and verification of the cover, double-height reinforcement placed in a 24 x 19 x 249 cm formwork

The pouring is then completed in three layers, which are compacted as they go. The beam is then levelled.

Figure 4-9: Concrete packing and distribution around reinforcement, pouring concrete and levelling

Finally, a dry mortar is prepared with the same proportions of cement, sand and earth as for concrete. It is placed on top of the beam to absorb the excess water and make the glaze.

Figure 4-10: Spreading of the dry mortar, smoothing, cleaning after the beam was removed from the mould

The beams are then cured several times a day for 28 days and left to dry for another week.

4.4 BEAM TESTING

We found out that the PEC beams are particularly fragile. Then they should not be moved for 4 weeks before testing. As well for the double height composite beams, they should not be moved for 3 weeks before casting the other side of the beam.

Figure 4-11: Plain PEC beam broken without load. As the crack is not centered, it might have been created by moving the beam.

The workability of the concrete is optimal when the slump measured is between 18 and 23 mm. Water has been added by small amounts until this range of value is reached, for each mix. The water cement ratio is always close to 1.50 for PEC beams and between 0.70 and 0.80 for PCC beams.

Casting with bamboo was not easily done. The reinforcing networks have to respect very precisely the cover needed on each side on the beam, which is tough because bamboo is never straight. Another problem was met while making the stirrups. We were thinking of bending them after heating the bamboo, but making a right angle was too tight and broke the culms.

Also, with PEC, if the tamping is not done properly on the sides of the beam it can easily make voids, as it did for the cylindrical samples. The first beams that were made had to be broken because of this.

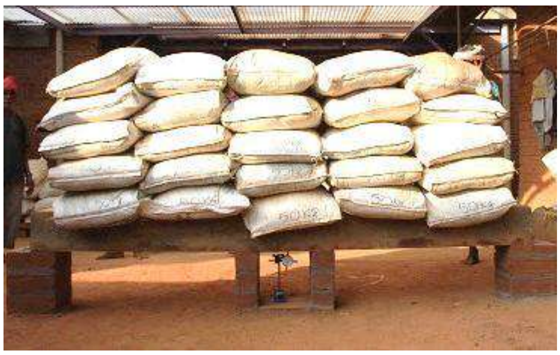
Although we did not make it to the point of failure, these tests were able to determine the overall behaviour of each type of beam. As the tests will continue until after my departure, an in-depth analysis of the results and the calculation of the flexural modulus will be done later. However, deflections were measured for each increment of the load and can be compared for each beam height. In order to protect the measuring device in the event of breakage, brick supports were installed under the beam in the centre. For each new crack, the load was noted and the evolution of the crack was monitored. We will start by looking at each model qualitatively, and then we can study the comparison of the deflections for each beam model.

4.4.1 Single height beams

Only this beam model could be tested to failure.



Figure 4-12 (Left to right):
- **Breakage of a single-height PEC beam**
- **Measurement of the width of the fault**
- **Breakage of a double-height PEC beam**
- **Breaking a double-height PCC beam**



Beam	**PEC**		**PCC**	
Height	Simple	Double	Simple	Double
Maximum load	175 to 250 kg	150 to 250 kg	450 to 750 kg	900 to 1250 kg

Table 4-1: Maximum load for each type of beam

Concrete beams are of course much stronger than earth concrete beams. It is difficult to quantify this difference because there is a great variability in the results. The ability to carry the load may also have been influenced by internal faults due to the displacement of the beam. There is no appearance of cracks before the break.

4.4.2 Double height beams

Steel reinforcement

Here only deflection could be measured. As the beams support large loads, the maximum load (here 3.75 tons) is limited by the achievable loading height (the whole becomes too unstable from a certain number of "layers" of bags). PEC beams deform much more than PCC beams and have many more cracks for the same weight.

Figure 4-13: Steel-reinforced PEC and PCC beams; load 3,250 kg (deflections 9.03 and 5.13 mm respectively)

Bamboo reinforcement

In this case, the beams appear to be extremely elastic. They do not break but crack a lot. The cracks are distributed over the central third of the PE beams (up to ten per double-height beam) and enlarge with the load, while the PCC beams have a large central crack for single-height beams and 3 to 6 faults for double-height beams.

Figure 4-14: Cracks distributed in the centre of a simple PEC beam (left); Full-width centre crack of a single beam in PCC (straight)

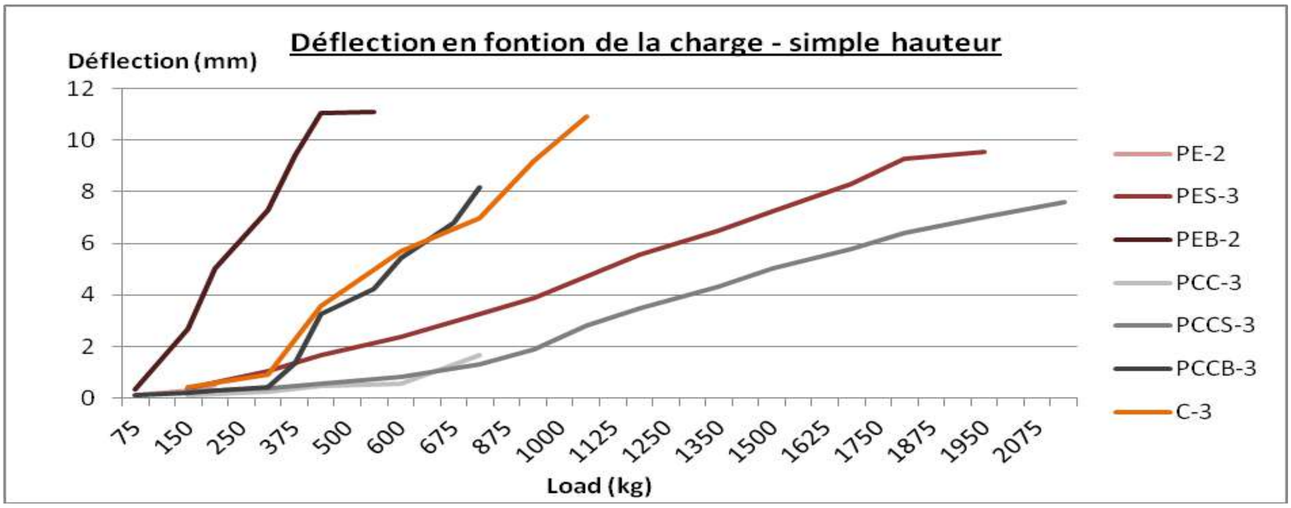
4.4.3 Composite beams

These specific beams of the Institute showed a great ability to deform without breaking since the load was limited by the maximum deflection measurable by the pressure gauge.

Figure 4-15: Single-height composite beam touching the central supports (deflection 10 mm)

4.4.4 Comparison of deflections

The graphs below allow you to compare the evolution of the deflections of single and double height beams for each type of beam.



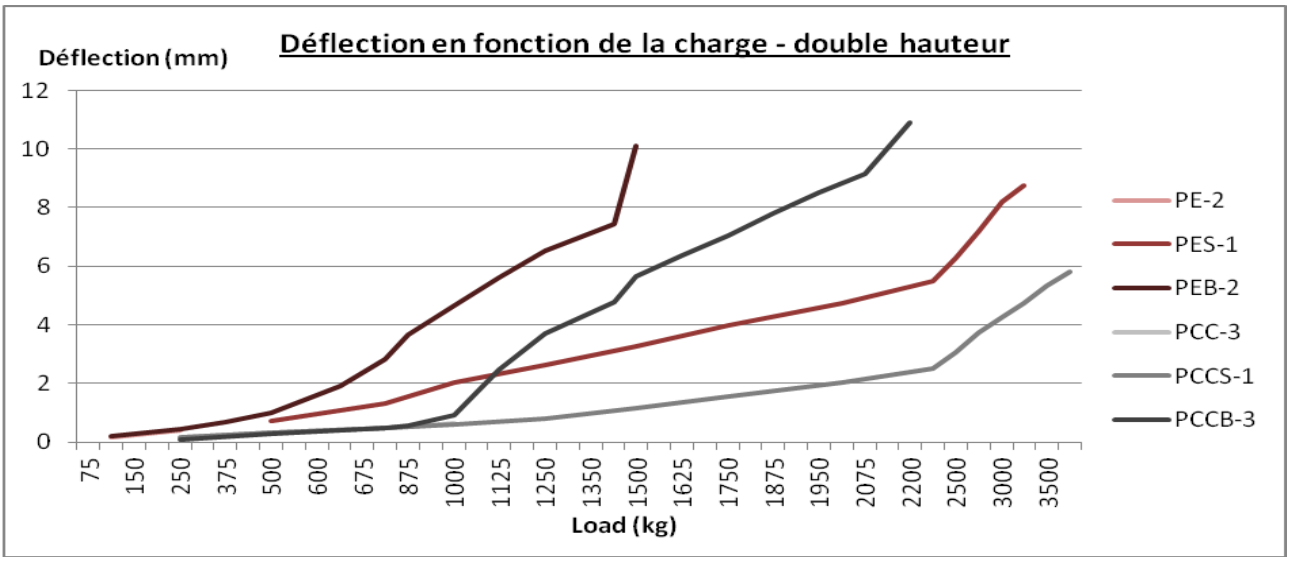


Figure 4-16: Load-dependent deflection changes for single and double height beams

Note: As averaging the measured deflections for each beam is irrelevant, a sample that seems to present representative results of the series has been selected for each type of beam to construct this graph.

Generally, the slope of the deformation is low up to a certain threshold where it increases abruptly. This threshold value is obtained for a much higher load for steel-reinforced beams than for other beam models, and it is the same load value for PE and PCC beams. These beams are the ones that flex the least. The graphs show very large deformations for beams with bamboo reinforcement. Simple composite beams deform in a manner comparable to single beams made of PCC.

4.5 TESTS ON SAMPLES

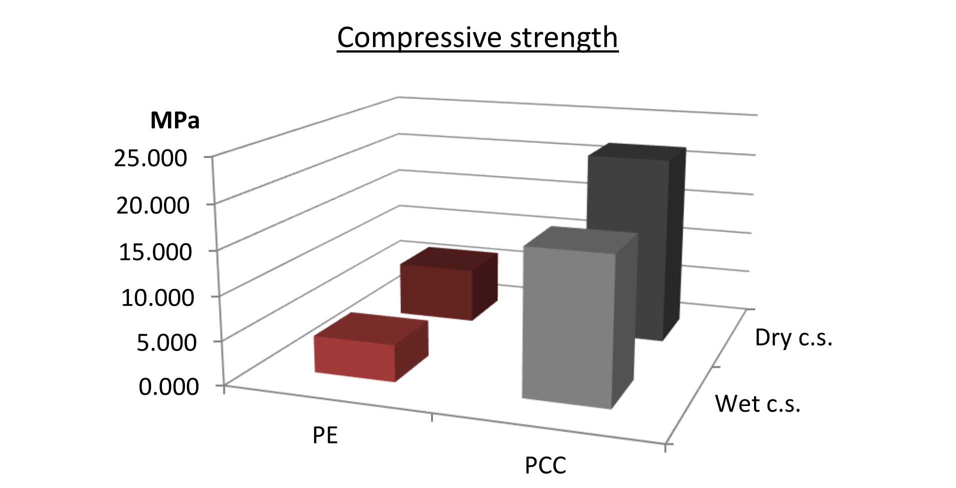
6 cylindrical samples have been made by type of mix. PEC and PCC compositions were as such:

Type of concrete	*Cement*	*Red soil*	*Sand*	*¼" gravel*	*½" gravel*	*Water/cement ratio*
PEC	1	1.5	3	2	5	1.53
PCC	1		2		4	0.71

Table 4-2: Mix ratio by parts of the volume for PEC and PCC

To get the same workability, a PEC mix needs twice more water than PCC. It could be because soil needs a certain amount of water to break the agglomeration of particles.

4.5.1 Compressive strength tests



	PE	PCC
Wet c.s.	4.222	16.454
Dry c.s.	6.418	21.728

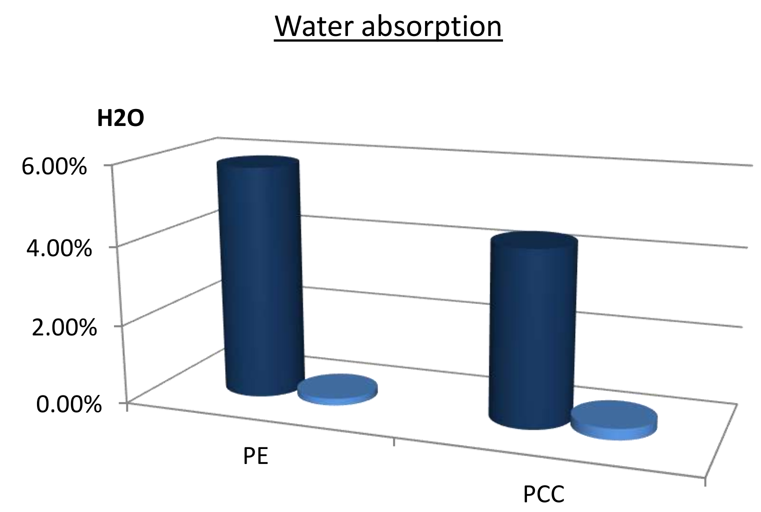
Sample	PEC	PCC
Density (kg/m3)	2239.61	2360.04

Figure 4-6: Compressive strength and density of PE and PCC

Unfortunately, PEC sample has lost about 50% of its c.s. compared to the similar mix ratio containing 1" gravels (6 MPa instead of 11 MPa in dry c.s., 4 MPa instead of 7 MPa in wet c.s.). C.s. of PCC is about 4 times that of PEC. Wet c.s. of PCC is 75% of its dry c.s., whereas wet c.s. of PEC is 65% of its dry c.s. PCC has higher density than PEC, but the difference is not enough to explain such difference in the c.s.

PCC seems less affected by immersion into water. PEC has definitely much lower performances than regular concrete, but such high values of c.s. are not always required in construction.

4.5.2 Water absorption



	PE	PCC
IMC Wet state	5.85%	4.37%
IMC Dry state	0.17%	0.28%

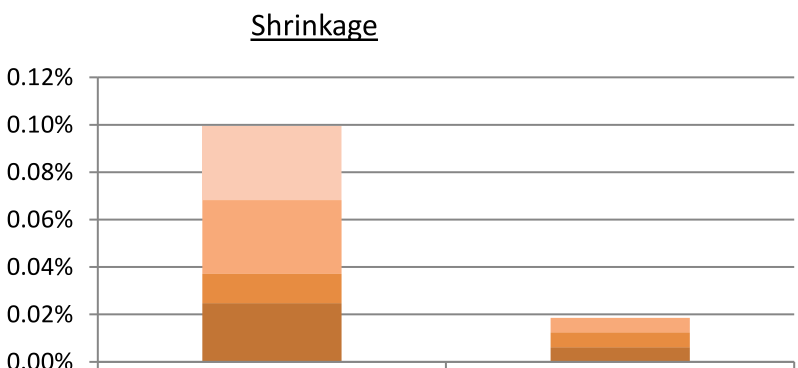
Note: IMC = Initial Moisture Content

Figure 4-7: Water absorption of PEC and PCC

Surprisingly, PCC seems to absorb moisture more than PEC while air-drying. But it is generally much less absorptive in water: water absorption of PCC is 75% of that of PE. Nevertheless, even water absorption of PEC is very low compared to the values obtained in Testing phase 1.

The very low water absorption of PCC could explain the small variation between dry and wet c.s. of PCC. Water absorption of PEC is very close to the value obtained in Testing phase 1; it is actually lower even If the density of the samples is not as high as previously. It could be due to the fact that curing has been done more regularly than for the first series of Testing phase 1, which has helped to stabilize better the samples.

4.5.3 Shrinkage



	PE	PCC
During oven-drying	0.03%	0.00%
During weeks 3 & 4	0.03%	0.01%
During week 2	0.01%	0.01%
During week 1	0.02%	0.01%

Figure 4-8: Shrinkage of PE and PCC

Total shrinkage of PEC is here 0.10% and 0.02% for PCC. Shrinkage of PEC continues in the last weeks of curing and the oven-drying, whereas PCC does not shrink at all after 24 hours in the oven.

These results confirm that even if the presence of soil induces shrinkage, it is possible to maintain it within the limits of acceptable values (in this case below 0.1%). These data raise a question about the point where shrinkage stops; it would be interesting to measure in a larger scale to see if it continues or not after the curing process.

Nevertheless, a criticism can be made about measurement of shrinkage here. It has been noticed during c.s. tests that PCC samples have lot of shear stress, probably because their surface looks concave even if they have been cast and finished properly. It could be because shrinkage mainly occurred in the centre of the cross-sectional area, and then measurement of shrinkage is wrong because the calliper measured the external height of the sample.

4.6 FLEXURAL STRENGTH

Note for discussion: The flexural strength can vary a lot according to the characteristics of the bamboo: fibres, drying process complete, etc. The distribution of the strength along the length of the culm can be irregular, having a great influence on the results of the tests also, which should not be seen as a consequence of the selected parameters only.

If the results are not satisfying with unmodified bamboo, additional samples could be made trying to improve the pull-out strength of the bamboo. Plangsriskul and Dorsano [5] suggest that a modification on the surface roughness of the bamboo, for example denting the surface or wrapping coils or ropes around the bamboo, could improve the bond with concrete. It is important to focus on this issue because the natural pull-out strength of the bamboo in concrete has been experimentally estimated as 2.34 MPa [5], against 8 MPa for steel. It could then be the main limitation to getting a great flexural strength with a bamboo reinforced beam.

REFERENCES

[1] Brink Rush (1966), Bamboo reinforced concrete construction.

[2] Ghavami (2005), Bamboo as reinforcement in structural concrete elements

[3] IJEAT (2013), Performance Evaluation of Axially Loaded Element using Bamboo as Reinforcement

[4] Alito (2005), Bamboo reinforcement as structural material for the construction of low-cost houses in Ethiopia

[5] Plangsriskul and Dorsano (2011), Materials Characterization of bamboo and analysis of bonding strength and internal strength as a structural member in reinforced concrete

[6] BYK Gardner, Epoxy Coat Test: http://www.allianceorg.com/pdfs/Epoxy_Coat_Test.pdf

[7] Khare (2005), Performance evaluation of bamboo reinforced concrete beams