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USE OF WOOD WASTE IN CONSTRUCTION OF CURVED LOW-COST ROOFS

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Abstract: This paper aims to find a cost-efficient solution for roofless shelters in Egypt by creating a curved panel using cement and wood composite. The panel shall be able to cover a span of 2.4 meters and should be used as a low-cost roofing element. Our scope entails three different tasks. First of all, the design of the wood-cement composite material in the curved panel is to be conducted carrying high compressive strength. The latter shall be done with the lowest cost and by investigating mainly the wood-cement ratio that is to be used and the grain size of the used wood particles. Secondly, analysis of the curved shape is to be conducted starting with a simple vault curve. Further parametric studies are to be done in order to obtain variability in the height, span, shape and thickness of the curved shape. Last but not least, the actual manufacturing of the obtain results is to be conducted using the CNC technique. The manufacturing will be done with foam blocks. To sum up, the project will consider three main factors; Mix design, Wood particles, Design of panels in order to obtain the highest compressive strength with the lowest cost. The panel manufacturing will take place using the CNC machine and Gasoline type of wood and will be used to serve as a low-cost roofing element.

1. Introduction

1.1. Literature Review

Different studies showed the success of mixing wood wool with Portland cement to obtain an economic alternative of bricks to be used in the masonry construction. One study tested the mixture of wood, cement and limestone. The tests that took place were compressive and flexural strengths, unit weight, and absorption. Scientists tend to have green criteria while investigating or studying a new topic. Conducted studies concluded that the wood cement composites are lighter in weight by 65% with a compressive and the flexural strengths with values of 7.2 MPa and 3.08 MPa respectively. In this study we are trying to find a new cheap solution for the roofless shelters in the poor countries. The design of the curved roof will fulfill the needed shelter. As the curved roof will be implemented in poor area, our main aim was to guarantee a lower cost than the reinforced concrete.

1.2. Background

Due to the current economic crisis invading Egypt, there exists a huge imbalance in the Real Estate sector serving the residential supply/demand chain. The latter is resulting from the overpopulation that is currently taking over. A huge percentage in Egypt is involuntarily suffering from informal housing mainly due to the lack of affordable roofing system. This paper's objective mainly is to provide an alternative cheaper roofing system using Wood-Cement waste. This mixture should be effectively accessible and sustainable to extend its function on the long-run. The Wood-Cement Composite should offer a general contribution to the global residential sector in worldwide.

1.3. Expected Outcome

This paper requires mainly obtaining an adequate mix design that serves its purpose successfully. Meanwhile, it should propose a suitable insulating alternative that is nevertheless cheaper with higher efficiency and accessibility. The expected outcome of this research paper should have relatively quick execution duration since it involves the prefabrication of a sustainable roof panel.

1.4. Scope of Work

The proposed research paper entails the trial and error of different mix designs and testing their results until a selected ratio is obtained. An analysis of the results is conducted to correlate them with the adequate standard format in order to successfully prefabricate the Wood-Cement Composite roof panels and complete its full-scale testing.

2. Mix Designs

Wood Wool Casuarina. This is because the wood wool Casuarina is much cheaper than all the other alternatives. Old references and researches were looked at while choosing the most adequate mix design and most acceptable quantities that would make wood and cement act as a good composite. Three mix designs were attempted and tested throughout the project's duration. Mix Design A was the first attempt and the quantities were taken from the literature review. Three different mix designs with three samples each were conducted with unsuccessful results.

2.1. Mix Design A

Table 1: Mix Design A

Sample	Wood (%)	Cement (%)	Water (%)	Total Mix Weight (grams)
A1	18.1	50.9	31	2320
A2	14.1	30.8	55	528
A3	15.8	42.1	42.1	475

After studying the results of the first mix design, it was deduced that the composite needs some kind of binding agent to hold the composite together. After doing some research, it was decided that a Binding agent (Gypsum) should be added to the mix to increase the bond between the particles and hold the composite together.

2.2. Mix Design B

Table 2: Mix Design B

Sample	Wood (%)	Cement (%)	Water (%)	Gypsum (%)	Total Mix Weight (grams)
B	13.3	28.9	40.3	20	496

B1	14	34.4	36.6	15	465
B2	14.2	35	35.5	15.3	552
B3	14.2	35	35.6	15.3	559

Later an addition of Gypsum was conducted to further investigate and later on a plasticizer was added. However, all results were unsatisfying.

2.3. Mix Design C

Table 3: Mix Design C

Sample	Wood (%)	Cement (%)	Water (%)	Plasticizer (%)	Total Mix Weight (grams)
C	16.1	30.1	40.9	13	465

2.4. Comparison of Mix Design Components

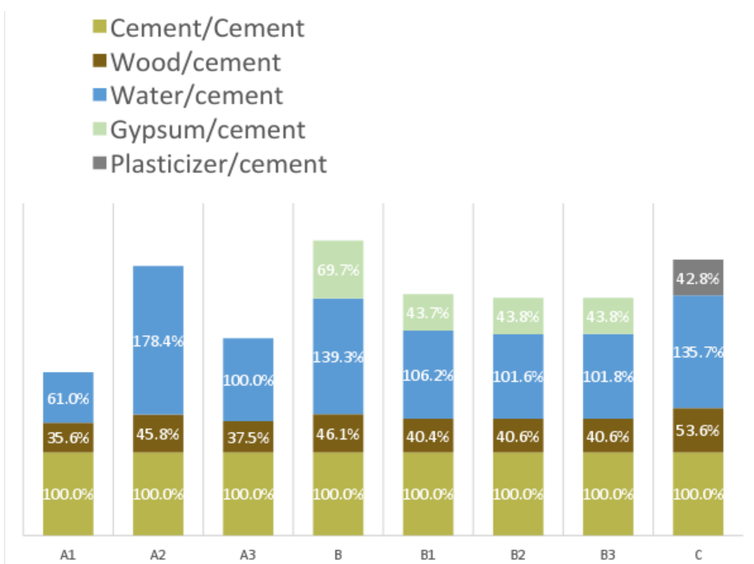

Figure 1: Comparison between Batches

3. Tests

3.1. Percentage Passing Sieve #200

Figure 2: % Passing Sieve #200

Table 4: % Passing Sieve #200

Initial Size (g)	Percentage passed from Sieve #200 (%)	Final Weight (after oven-drying) (g)
200	15	170

We used the Casuarina wood wool instead of sand as our fine aggregate in our mix design; therefore, we did the sieve analysis as if we are examining sand. The results obtained explain that only 15% passed sieve #200 which explains that wood wool properties is fairly good.

3.2. Compressive Strength (BS180-200)

Figure 3: Compressive Failure of Selected Batch

Table 5: Compressive Strengths & Costs

Batch	Sample	Compressive Strength (MPa)	Cost/m³ (EGP)
B	S1	1.07	238.6
	S2	1.01	
	S3	1.06	
B1	S1	3.81	203.6
	S2	1.55 (neglect)	
	S3	2.83	
B2	S1	2.36	244.2
	S2	2.03	
	S3	2.11	
B3	S1	1.88	244.2
	S2	1.51	
	S3	2.22	

Tests were conducted using MTS machine. In conclusion, sample B1S1 had the highest compressive strength compared to other samples (= 3.81 MPa). Therefore, we have chosen this mix and then we proceeded to do the flexural strength test. According to cost calculations, B1S1 also concluded to be the lowest cost mix.

3.3. Flexural Strength (ASTM C78)

Using the MTS machine, according to the succeeded compressive strength sample, we chose the mix design of B1S1 and then we poured six beams using the 3-point test. In conclusion, the sample got +0.67 MPa of ultimate Tensile strength.

Figure 4: Tensile Failure of Selected Batch

Table 6: Ultimate Tensile Strength

Batch	Ultimate Tensile Strength (MPa)
B1	+0.67

3.4. Comparison between results

This graph shows briefly the compressive strength of all the samples we tested in our thesis. A1, A2 & A3 samples consisted of (wood wool, cement, & water only) the graph shows that their compressive strength were low. B, B1, B2, &B3 samples consisted of (wood wool, cement, gypsum, & water) the graph shows that most of these samples are relatively higher than that of samples A, and it is clearly visible that same B1 has the higher compressive strength. Sample C1 consisted of (wood wool, cement, Plasticizers type D & water) but sadly it had a very low compressive strength.

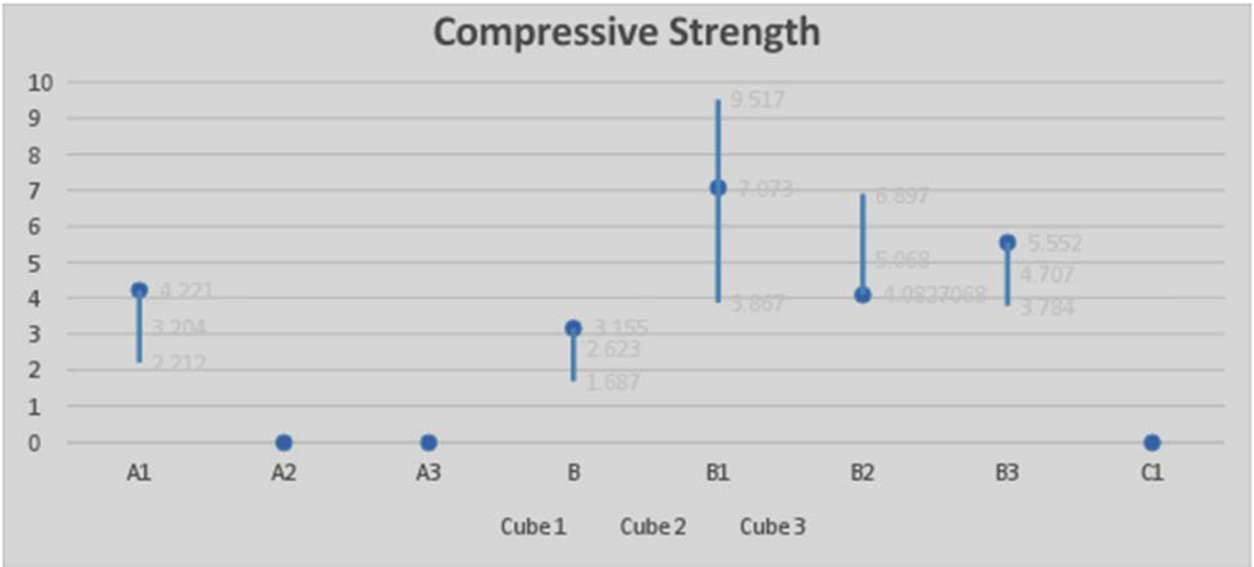

Figure 5: Comparison between Different Batches

4 Fabrication

4.1 SAP Analysis

As in the Table below, a total of 9 models were drawn on SAP for analysis. The SAP analysis was done to get the maximum compressive and tensile stress applied on the models. The unit weight of wood cement composite was 12.16 kN/m^3 and the modulus of elasticity was 12.2 MPa. The target of the SAP analysis during this phase was to analyze the models by adding their dead load (which consist of the materials' own weight) and the live load (assumed to be $1kN/m^2$, corresponding to the inaccessible roof as in the ECP). A comparison of the models with the ultimate compressive and tensile stresses (obtained from different mix designs tests) was made. Model #4 was selected to fabricate, as it has the lowest maximum tensile stress (0.80 MPa). The figure below shows a sample of the SAP models.

Table 8: Maximum Obtained Results

Model #	Height (cm)	Thickness (cm)	Max. Compressive Stress (MPa)	Max. Tensile Stress (MPa)
1	100	12	0.68	0.99
2	100	10	1.18	1.36
3	100	8	3.00	2.35
4	70	12	0.93	0.80
5	70	10	1.64	2.56
6	70	8	1.96	2.36
7	30	12	0.71	0.82
8	30	10	3.21	4.18
9	30	8	0.52	2.19

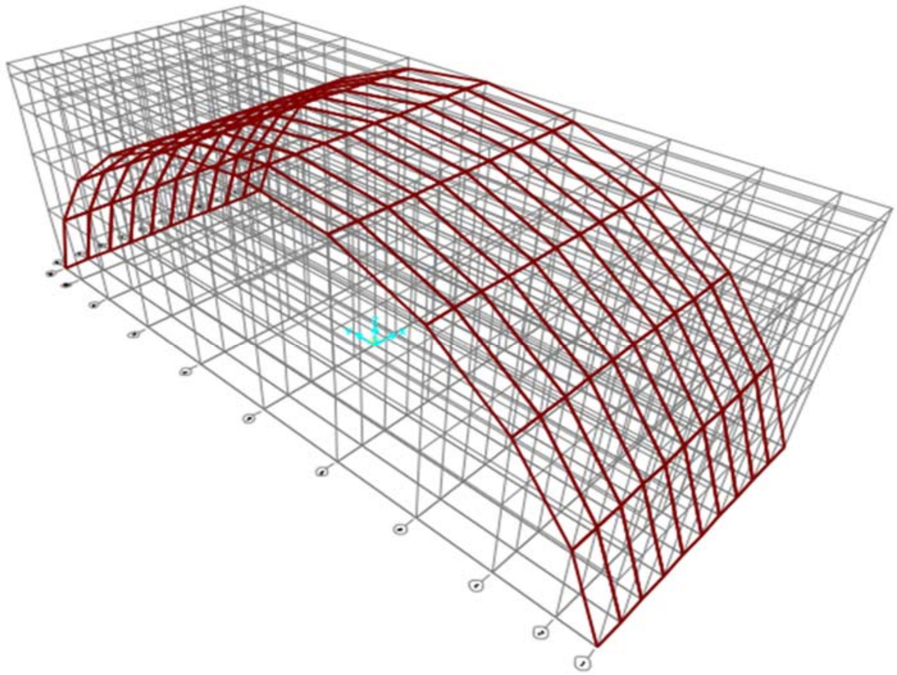

Figure 6: Curved Shape using SAP

4.1 CNC Machine

One of the main outcomes of this research is to have sustainable panels that can be easily fabricated, transported and installed. That is why the selected mix will be poured on a form made of foam that can be used several times and mobile. Also, the curved shape of the panel is challenging, consequently the foam's shape is to be routed using the Computer Numerical Control Machine (CNC). The form 3 dimensional model is made on Rhino according to the dimensions obtained from the SAP analysis. This model is then imported on ArtCam to specify the cutting order for the CNC machines in a G-Code form that contains x, y, and z coordinates of the machine movement. ArtCam is also used to determine the way of movement (offset, parallel, 3D offset), and the location of zero point. Then the G-Code is used on the machine which its main challenges involve operating on a 15 cm depth. As a result, the method of slices is used. The latter consists of having slices of 4 cm, resulting in 16 G-Code files that can reach up to duration of 36 hours each, which is inefficient. In order to decrease the cutting time and the exerted effort, cutting machines containing hot wires or wood are used. This method is also applied on vertical slices as much as horizontal ones. Connecting the foam slices was a big challenge since the use of polyvinyl acetate (heat glue) resulted in the shrinkage of the slices. Consequently, the use of double-face glue tape was a success along with long toothpicks.

Figure 7: Polyvinyl Acetate

Figure 8: Vertical Slices

4.2 Pouring

Below are the exact quantities for each component used to pour one curved panel.

Table 9: Pouring Quantities

Component	Quantity
Cement	168 kg
Water	170 kg
Wood	67.2 kg
Gypsum	71.4 kg

Figure 9: Curved Sample After Pouring

To maintain the 12cm thickness of the roof, 12 cm marked on the BBQ sticks were used on all the surface of the foam formwork, and a marker is used to draw the curve on the sides of the foam formwork. Also foam boards with wood shoulders were used on the surroundings to avoid side leakage.

4.3 Compaction

A steel rectangular rod was used along with manpower in compacting in order to reach the desired thickness which is 12 cm.

4.4 ManPower:

The roof panel requires four men to mix and pour. Three unskilled and one skilled would get the job done ideally.

4.5 Final plate (less than 0.5 cm):

A plate of mortar was added on the top after compaction to lessen the crack and act as an insulator to protect the panel. Plastic sheets covered the curved roof to prevent humidity, which may negatively affect the final results. Moreover, it acts as a self-curing method.

Figure 10: Curved Sample During Curing

5 Sap Model vs Real life Model

The real life model failed at 18.82 kN, and its ultimate compressive strength and ultimate tensile strength are 6.65 MPa and 1.17 MPa respectively. We then applied the same load of 18.82 kN on the SAP model, to get the maximum compressive and tensile stresses, which are 1.80 MPa and 1.29 MPa respectively. As you can see, the failure was because of the tensile stress.

Table 10: Comparisons in Obtained Results

Roof Type	Real-Life Model (material)	SAP Model
Load of Failure (kN)	18.82	18.82
Compressive Strength (MPa)	6.65	1.80
Tensile Strength (MPa)	1.17	1.29

6 Cost Analysis

Cost analysis was based on materials' cost comparison between the WCCRP and the RCRF (a straight slab with 8 cm in thickness, and with a minimum reinforcement). This table of comparison shows that there's a huge difference in Material costs between the WCCRP and the RCRP. It shows that the cost/m2 of our mix saves 124 EGP compared to the RCRP cost/m2. Moreover, Cost/panel according to our mix, saves 235 EGP compared to the RCRP. The cost of labor of the RCRP absolutely costs more than that of the WCCRP, as in the RCRP, more labors are needed such as; steel fixer, carpenter, skilled & unskilled laborers, but in the WCCRP, only 4 labors are needed; three unskilled and one skilled. Regarding the Formwork cost comparison, in the WCCRP we used foam; which costs 60 EGP/sheet. And the panel required 50 sheets of foam plus the glue and tape to bind them together; so it costs 3600 EGP. This cost is not per panel; it will be divided by the number of panels poured inside that foam formwork. Our panel is prefabricated panel as it is poured outside site, in contrary of the RCRF. So the RCRP formwork is made of wood, which needs to be delivered to the site and it also needs a carpenter to bind them together which will cost more money compared to the prefabricated WCCRP.

Table 11: Comparison in Both Roof Types

Type	WCCRP	RCRP
Material Cost (LE)/ m^2	104	228
Cost (LE)/Panel	336	571
Money Saved (EGP)	124 LE/m^2 & 235 LE/panel	

7 Challenges Encountered

The CNC machine is very complex and not easy to operate. The team managed to work with the lab technicians to learn how to use it with its optimum efficiency. Due to the fact that there was multiple mix designs, there was a lot of experimental work that should've been done in a critical amount of time. However, it was managed properly and the experiments that required repetition were repeated and results were gathered on time. The formwork that was designed was very large, difficult to move, replace and it wasn't as tough as any other formwork so dealing with it was very challenging. Time was the biggest constraint throughout the whole project. In just 4 months it was required to come up with an adequate mix design, test it, analyze the whole design using sap, fabricate a panel and do full scale testing on it. This was the most challenging part, as this project is not minor, however the team managed to tackle that issue and finish on time and come up with the best results. It was calculated that the mix should be 120 kg of cement, 48 kg of wood wool, 51 kg of gypsum, and 125 kg of water. It was then realised that these weights weren't enough to cover all the volume required. Therefore an additional 40% for each component was added to ensure that this would be enough to pour and finish one panel. Moreover, another obstacle faced was that the mixer didn't fulfill the entire amount required in one round, so the components had to be mixed in three rounds. This wasted a lot of time. What is more, pouring the curved roof panel into three rounds was not as accurate as pouring the whole roof panel in one round. This has actually lead to very minor cracks between the poured layers of the three rounds.

8 Conclusion & Recommendations

In this project, the obtained curved panel roof is composed from an adequate mix design that is composed from wood, cement, water and gypsum. The selected mix is B1, as it has the highest tensile and compressive strengths. After analyzing 9 models on SAP with different thicknesses and heights, the best model will be selected according to the minimal tensile stresses. The selected model has a height of 70 cm and a thickness of 12 cm, so our model is higher in height. The formwork fabrication is made from foam using the CNC machine to be able to maintain the curvature of the model, to be easily transported and to be used several times. The main objectives of this project are to have a low-cost alternative and sustainable roofing system compared to the current roofing systems available. The material cost of the WCCRP is less than the RCRP by 124 Egyptian Pounds per meter square. The panel can be prefabricated on-site or somewhere else, it was also found that our panel is machineable and that could have further uses in the industry. The main reason our roofing system is curved is to reduce tension in the panel and to avoid settlement of rain and dust. The main characteristics and advantages of the roofing system is that it is made of new materials, new shape, and a fabrication technique with a lower cost. This work needs further future work to enhance the performance of the roofing system. Although, the curved panel provides better insulation compared to current roofing systems, it was not studied nor tested, however, it is recommended to add a small layer of foam for insulation and layer of bitumen for protection. The sample was not tested for shear stress, so shear test need to be conducted to be sure of the failure mode. Also, a bigger mixer is needed to avoid pouring on different stages and a stiffer covering alternative instead of nylon. Finally, it is advised to try alternative curve shapes and parabolic shapes. The fixation of the panel was not part of our scope and it need to be studied.

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