Concrete for 3d Printing Technology Using Coir Fiber and PET Resin

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***Abstract*—The development of science and technology is undergoing speedy growth. And the construction should be also changed in the current digital transformation. Concrete 3D printing is a new technology in the construction industry. It contributes to modernization based on new and cut-edge characteristics. This new technology saves considerable labor as well as costs. Thus, the material used in concrete 3D printing plays an important role. Because concrete is a mixture of many components that meets the requirements of the concrete 3D building structure. Recycled PET resin and coir fibers are mixed into concrete to replace other aggregates in this study. The use of recycled and natural waste from various commodities in concrete 3D printing is an appealing and safe disposal strategy. The idea of using recycled PET resin and natural fibers as raw materials for concrete comes from the problem of environmental pollution. This method can reuse waste from PET resin and other resins with similar properties to it. That can solve the majority of the environmental issues created by recycled materials. In addition, using natural fibers is also a current trend to protect the environment. The material tests and experiments on concrete 3D printing buildings have been evaluated and showed good results.**

***Index Terms*—natural materials, recycle materials, coir fiber, PET resin, 3D printing, additive manufacturing**

I. Introduction

Concrete 3D printing is an additive technology that uses concrete materials to build the construction structure. The material element plays an important role. In the world, there are researches on the characteristics of polyethylene terephthalate (PET) on the properties of concrete [1]. Besides several pieces of research showed the evaluation of biosynthetic materials reinforced like coir fibers [2]. The references [3-4] described experimental researches of thermomechanical properties of recycled PET fiber reinforced concrete and 3D printing of granular layers in concrete construction. Printable properties of adhesives used in concrete 3d printing have also been given in the material [5-6]. There have been researches to evaluate PET materials in 3D concrete printing technology [7]. For 3D printing technology, materials play an important role in affecting the building structure. This research presents a concrete mix formula suitable for projects involving concrete 3D printing. In this research, the properties of concrete are improved properties of concrete for 3D printing by adding coir fibers and PET fibers. This paper presents the mechanical properties of concrete affecting layer ability and properties of concrete when adding admixtures, PET resins, coir fibers. The experiments on concrete 3D printing structures are analyzed and evaluated based on the properties of concrete. The material mixing ratio affects the 3D printing ability as well as the properties of concrete. The experimental tests are for evaluating the properties of concrete materials with variable adding additives, PET resin, and coir fiber to meet 3D printing requirements. The building structure was printed layer by layer in the vertical direction, then mechanical tests are carried on their samples. Finally, the results show the optimal formula of concrete materials for 3D printing. Concrete 3D printing has not replaced the necessity for construction employees, but they have made their work easier and safer. Using recycled plastics in concrete not only helps the environment but also enhances the performance of the concrete. Due to the low specific gravity of recycled plastics, partial substitution of natural aggregates such as sand with recovered thermoplastic trash can reduce concrete weight. One of the benefits of lightweight concrete is that structural components are less in size. There are two reasons why we chose to use PET and coir fibers in the making of concrete. The first is that this is a friendly concept. During the process, these recycled and natural materials are not transformed into other pollution like chemical or air pollution [8].

Concrete 3D printing is a technology introduced by many researchers around the world. There is a promising industry in the construction industry. But the biggest challenge is the materials used to print. Concrete is a used material in construction due to its unique properties. Outstanding is the ability to form and adhere high, can form a material flow for convenient transportation, high bearing capacity when cured, can link many materials together to meet requirements bridge using. For traditional construction technology, concrete is a material that meets the properties of the project. Although for a new field such as 3D printed concrete technology, it is necessary to add some special properties to meet the requirements of fabricating a complete 3D printing materials project. To improve these two important properties, the first method is to add additives to the concrete. Besides, several other materials can also improve the properties of traditional concrete to meet the 3D printed concrete fabrication requirements. That is coir fiber-natural material and the

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PET particles. These two materials not only improve the properties of traditional concrete but also improve the environment. This is a solution to help to reduce a large amount of PET plastic to improve the environment. Besides, natural materials are used.

II. Additive Manufacturing in House Building

Additive manufacturing is a process where the material is extruded from the extruder. 3D objects are created by extruding layers of material stacked on top of each other. The process works by computer control. The materials utilized in 3D printing technology are not constrained to plastic and metal. Rapid advancement in the area of concrete 3D printing demonstrates that there is unrealized potential in constructing economic buildings. 3D concrete printing is a type of additive manufacturing that allows completely new shapes to be created in buildings or structural components that were before not possible using standard concrete formwork. While concrete 3D printing will not completely replace existing building processes by tomorrow. But the benefits of the technology are obvious. Designing and building a home can be a costly and time-consuming job. This is why concrete 3D printing is an enticing option for builders and architects. Concrete 3D printing is based on fused deposition modeling (FDM). The biggest difference is the input materials. In this study, concrete was extruded to build the wall structure of a house.

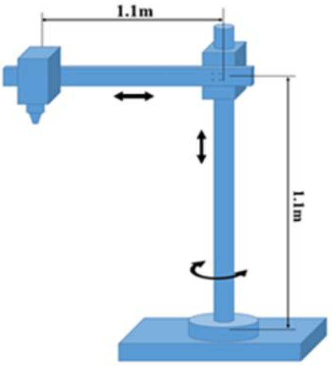

Figure 1. Mechanical structure of concrete 3D printing.

The structure of 3D printing operates using a cylindrical manipulator with a mechanical structure as shown in Fig. 1. The manipulator has 3 degrees of freedom. The first joint is a revolute one at the fixed frame to generate a rotating angle about the axis of z. The x-axis is defined by the length of the arm which is used for moving the extruder centripetally. The rotation angle is defined by the distance between rails on opposite sides. Two prismatic joints of the manipulator make up the cylindrical workspace base body with the height and length of the rectangular area. Therefore, the end position is defined by the extension of the arm attached to a concrete extruder.

A 3D printing is a method of creating prototypes by making layers of the designed object, then printing each layer on top of each other to create the object. 3D printing can be understood as an additive technology to create objects from designs on computer software. Similar to the 3D printing method that has been used in the medical, fashion, decorative,... 3D printing in the construction field is also additive technology. But the construction 3D printing application is still new, mainly used to create walls for a house or decorative objects with designs on computer software using concrete materials. The part similar to the house or decorations after designing on the software will be cut and printed on each layer of concrete stacked on top of each other to achieve the desired texture. Because 3D printing in construction is mostly used for the construction of the wall of a house, the roof is not mentioned in the content of this article. A house built by concrete 3D printing method must ensure the stability of the wall, the wall after printing must not be slanted to ensure the original design. Unlike ordinary concrete, the materials used for printing 3D concrete must be high-strength concrete. More precisely, concrete ensures a ductility that matches the speed of the extruded as well as the cross-section of each print, setting time, formability after each printing layer, and durability after complete curing. Conventional concrete does not guarantee the above properties, so the specific goal is to improve the properties of concrete to meet the requirements of concrete for 3D printing.

III. Novel Materials for Additive Manufacturing

As described in the introduction to the 3D printing method of concrete applied in building materials. The Material plays an important role in the feasibility of the project. The material for printing, specifically for this study, is high-strength concrete, which must have ductile properties suitable for the moving speed of the extruded. Besides, the concrete after being printed must be shaped and stable so that the next printed layer can be stacked. The process is continuous to create a structure that corresponds to the design. Curing time is also one of the factors that greatly affect the structure of the design after printing. If the curing time is too long, the stability of each printed layer is not guaranteed, leading to deviations from the designed structure. In contrast, the curing time is too fast, causing cracking in the structure after printing. These properties of conventional concrete are not suitable for 3D printing applications. Therefore, admixtures are used to enhance the properties of concrete.

A. Characteristics of PET Resin Material

The PET is a synthetic linear polymer with a chemical formula $(C_{10}H_8O_4)_n$ and is a kind of flexible plastic. PET resin is often used in cans and bottles containing food and water. PET resin is a component that can create high-strength concrete for concrete 3D printing requirements. Outstanding feature:

- It has good ductility at low temperatures.
- It has high durability.
- It has low water absorption.
- It is insoluble in water, dilute acids, neutral salts, and oils.

The value of tensile modulus is 2 – 4 (GPa). And Tensile Strength is 19 MPa. These are two outstanding mechanical Properties that help improve the properties of concrete.

Because PET has the outstanding properties mentioned above. It should be used to harmonize material applications for 3D concrete technology. In which the most outstanding feature is the ability to keep the original shape. This superiority of PET is the method of preventing shrinkage of concrete after extrusion.

After extrusion from the nozzle, the concrete enters the curing process. During this process, the concrete will show shrinkage due to the hydration process. The shape of concrete would change much without PET. Therefore, PET can enhance the properties of concrete applied to 3D printing technology.

B. Characteristics of Coir Fiber Material

Coconut is an extremely useful tree that is grown a lot in Vietnam, Thailand, and Brazil. Parts of the coconut tree are used for many different purposes. Coir fiber is obtained from the coconut shell after it has been dried. Coir fiber is used for many applications such as making ropes, handicraft products. Outstanding features:

- It has rigidity and lightweight.
- It has the ability to insulate.

Coir fiber is mainly composed of cellulose with a rate of 36-43% as researched [9]. Cellulose has the chemical formula $(C_6H_{10}O_5)_n$ found in all natural fibers. With a high cellulose ratio, coir can increase the insulation ability of concrete after curing. Besides, if coir can become a component of concrete used for 3D printing technology, it will be beneficial to the environment. That will make efficient use of natural fibers in the construction.

C. Combination PET and Coir Fiber Material

Ordinary concrete does not meet the characteristics used for 3D printing purposes with the main ingredients as shown in Table I. Therefore the addition of PET resin, coir fiber, and superplasticizer will be the solution. Besides improving the properties of concrete materials, using granular PET resin and coir fiber makes sense for the environment when using natural materials and using used PET resin. Concrete will have improved durability when there is a PET resin component in the mix formula. Due to the high strength of PET plastic, the good low-temperature ductility described in the previous section creates a bond between the materials. In addition, the PET resin helps to increase the stability of each printing layer, ensuring the ability to shape when the next print layer is placed with a chemical reaction (1).

$$(C_{10}H_8O_4)_n + nCa(OH)_2 \rightarrow nC_2H_6O_2 + nCaC_8H_4O_4 \quad (1)$$

The ductility of high-strength concrete is significantly enhanced when the mixture contains superplasticizers, reducing the curing time as a research [10]. Besides PET resin, coir helps concrete improve thermal insulation properties due to fiber properties. Since then, the wall after construction contributes to making the house more environmentally friendly, reducing the use of energy for the cooling system with chemical reactions (2) and (3).

$$(C_6H_{10}O_5)_n + nCa(OH)_2 \rightarrow nCa(C_6H_8O_5)_n + 2nH_2O \quad (2)$$

$$Ca(OH)_2 + SiO_2 \rightarrow CaSiO_3 + H_2O \quad (3)$$

TABLE I. CHEMICAL COMPOSITION OF PORTLAND CEMENT.

Element	Portland Cement by weight (%)
CaO	64.6
SiO_2	21.3
Al_2O_3	5.6
Fe_2O_3	3.3
Others	5.2

IV. EXPERIMENTAL SETUP

A. Manipulator and Extruder for Building

Figure 2. Manipulator and extruder used for research.

For material testing, the project uses a cylindrical coordinate robot arm with three degrees of freedom to create a trajectory for the design structure as shown in Fig. 1. With the Manipulator operating space, the maximum wall height can be printed 1.1m. The manipulator has a worksheet that uses a screw to extrude the concrete to create a print line as shown in Fig. 2. If the wall is larger then the robot's operating space will be divided into several parts to print and then assemble to complete the final product. In this study, a extruder was used to extrude concrete to create printed layers.

B. Structure of Wall for Automation Additive Manufacturing

In this project, the wall section is designed with two parallel prints to form the outline of the structure, the two prints are connected by support lines as shown in Fig. 3. Each print line measures 40mm wide x 20mm high, two parallel lines 170mm apart from the center of each print. Thus, the structure of the wall section will have free space as shown in Fig. 4. These gaps are intended to contain insulation materials such as rice husks, natural fibers used to insulate the house, contributing to making houses built with concrete 3D printing is more environmentally friendly. In addition, with the empty spaces of the wall structure after completing the concrete 3D printing work, reinforcement will be added to connect the wall sections to ensure the horizontal shear resistance of the structure.

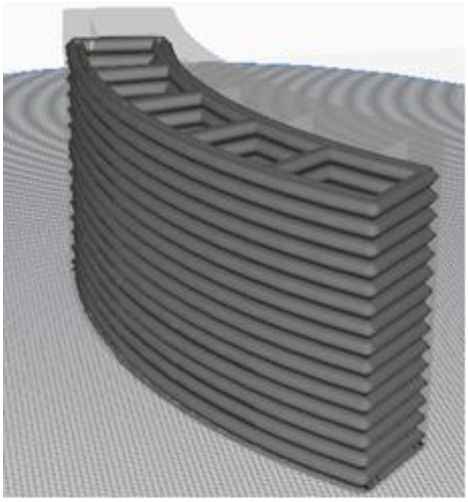

Figure 3. Modelling of wall structure.

Figure 4. Actual wall structure after completion by concrete 3D printing.

C. Experimental Hardware and Software

For this study, the output of the extruder is a circle with a diameter of 34mm corresponding to a travel speed of 50 mm/s of the extruder and a flow rate of 0.16 m^3/h. To evaluate the durability of the wall after 3D printing, each printed layer will be measured for height, slump, and formability after 28 days. Besides the statistics of the size and shape of the printed layer over time, the compressive strength of high-strength concrete is calculated based on the empirical equation [11].

$$f_{cm}(t) = \beta_{cc}(t).f_{cm} \tag{4}$$

$$\beta_{cc}(t) = \exp\left\{s\left[1-\left(\frac{28}{t}\right)^{0,5}\right]\right\} \tag{5}$$

Where: $f_{cm}(t)$ is average compressive strength of concrete after t days; f_{cm} is average compressive strength of concrete after 28 days; s is coefficient depends on cement grade and concrete grade.

In addition, the composite was tested for compressive and flexural strength in parallel with the printed layers as shown in Fig. 5. Two concrete samples containing PET resin and non-PET resin were compared. The size of each test sample is 40x100x200 mm corresponding to 5 printing layers.

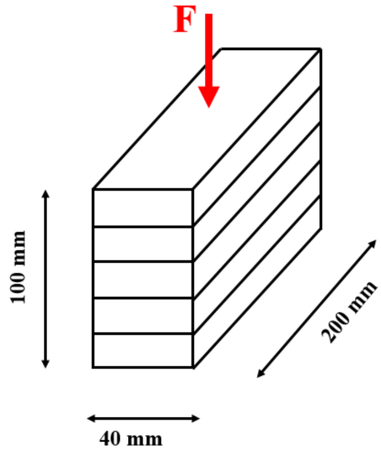

Figure 5. Dimensions and direction of the force in the test.

D. Experimental Parameters for Additive Manufacturing

TABLE II. MATERIAL COMPOSITION USED.

Material	Requirement
Cement	PCB40 standard TCVN 6260-2009
Sand	Particle size <2.5mm
Water	
Gypsum powder	
Superplasticizer	
Granular PET plastic	Size <2.5mm
Coir fiber	Length <10mm

To create high-strength concrete to meet the requirements of 3D printing of concrete in the research project with the materials shown in Table II. For cement, this study uses PCB40 according to TCVN 6260-2009 standard for compressive strength of 40 MPa after 28 days. The admixture used to create flow for high-strength concrete is a superplasticizer. For sand choose grain size <2.5mm for all different mixing ratios. With different mixing ratios, Table III presents the comments when experimenting. From the results of the experimental process, find the optimal formula to meet the requirements of 3D printing of concrete.

The results of the tests are shown in Table III. *C1* has a composition of cement, sand, and water giving a loose, unformable mixture. *C1* cannot be used as a material for concrete 3D printing technology. To eliminate the looseness of *C1*, gypsum and superplasticizers are added. But gypsum accounts for a high percentage, so *C2* is dry and the rheology is not high. Mixture *C3* has less than half agar ratio than *C2* and has no superplasticizer. *C3* becomes tacky, sticking to the pipe leading to difficulties in the extrusion process. Next, the *C4* mixture has the same material composition as *C3* and is supplemented with superplasticizers. The results obtained with the *C4* mixture are positive. *C4* has high formability after extrusion, suitable rheology, and greatly reduced adhesion to pipes. Based on the composition of the *C4* mixture, PET resin and coir fiber are added. Mixture *C5* gives the same results as *C4* with the proportions of PET resin and coir fiber as shown in Table III.

TABLE III. EXPERIMENTAL MIXING RATIO OF MATERIALS.

Name	Cement (kg)	Sand (kg)	Gypsum-powder (kg)	Water (l)	PET (kg)	Coir fiber (kg)	Super-plasticizer (l)
C1	25	50	0	20	0	0	0
C2	50	50	40	20	0	0	0.13
C3	50	25	20	20	0	0	0
C4	50	60	20	20	0	0	0.13
C5	50	60	20	20	0.5	0.5	0.13

V. EXPERIMENTS AND DISCUSSIONS

The study considered several walls generating 3D buildings for experiments. According to Equation (1), the average compressive strength increase of concrete is shown through the graph of the relationship between the age of concrete and the average increase of concrete strength in Fig. 6.

The average compressive strength of concrete increased over time, from day 1 to day 15 the average compressive strength of concrete increased at a faster rate than the period from 15 days to day 28 of the curing process. From the comments on the results of the material mixture after testing presented in Table II. The two mixtures *C4* and *C5* give the best results with the ability to shape after printing and meet the requirements of extrusion in concrete 3D printing. The plasticity of concrete in mixture *C4* and *C5* is improved than that of mixture *C1*. Experimentally, the printed layers when using the *C1* mixture after printing the stacked concrete layers show signs of deformation and will fall when printed to the fifth layer corresponding to a height of 100mm as shown in Fig. 7. Superplasticizers create flow for high-strength concrete to meet 3D printing requirements in construction. Using natural and recycled fibers instead of aggregates has also been shown to be an efficient method of preventing the formation of microcracks in concrete. The additional recycled PET, as well as coir fibers, are used to increase the efficiency of plastic recycling, ensuring that the compressive strength of concrete is constant or even improves. In addition, when comparing the product after extrusion between the mixture *C1* and *C2*. For the *C1* mix, do not use gypsum powder, which makes the mixture uncontrollable and does not control the flow of concrete. The structure after printing appears deformation and subsidence as shown in Fig. 8.

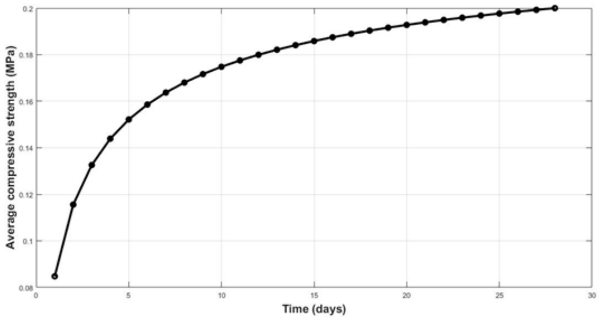

Figure 6. Relationship between average compressive strength and dried concrete days.

Figure 7. The phenomenon of structural failure is due to the material mixture not achieving plasticity.

For the *C2* mixture, gypsum powder is added to improve the formability of the concrete. But the weight ratio is too high, which causes the mixture to harden quickly, the printed mixture gives an unstable flow, and cracks appear on the printed layer. A mixture that is too dry after printing will appear delamination between the printed layers, breaking the strength of the structure. Gypsum powder is the solution to improve the formability of concrete if mixed with the right ratio. The addition of coir fiber to the composition of materials used for concrete 3D printing is possible when comparing the two mixtures *C4* and *C5*. The addition of these two materials does not affect the extrusion capacity of the extruded. The wall part after printing ensures the connection between the layers and keeps the design structure as shown in Fig. 9 (a) and Fig. 9 (b).

Figure 8. Deformation of the printed layer without gypsum powder.

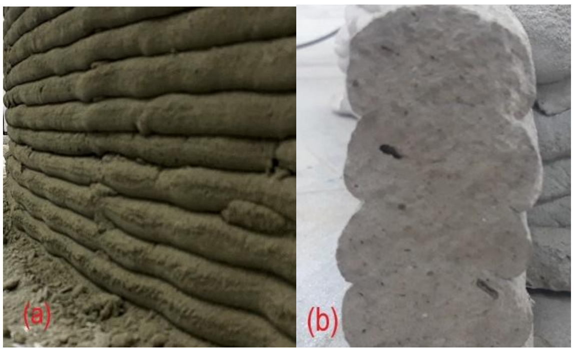

Figure 9. (a) The printing layer ensures formability when using the C4 mixture when printing is finished. (b) The printing layer ensures formability when using the C4 mixture after 28 days of the curing process.

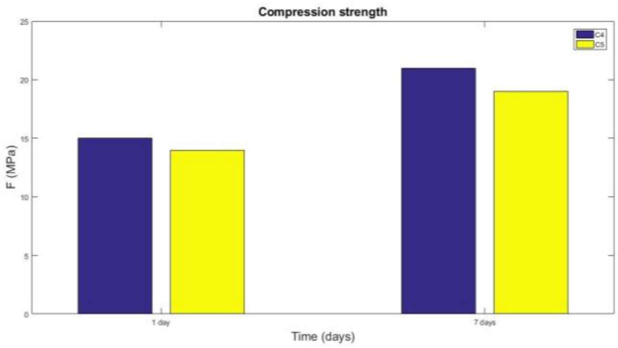

Figure 10. Compressive strength after 1 day and 7 days.

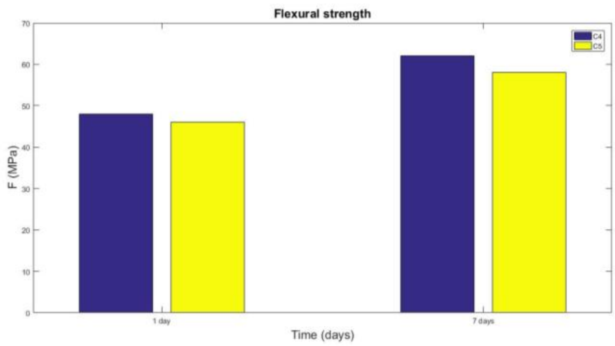

Figure 11. Flexural strength after 1 day 7 days.

The compressive strength of the test specimen is shown in Fig. 10. The flexural strength of the test specimen is shown in Fig. 11. All test specimens have their compressive strength and flexural strength determined in two timelines. It is day 1 and day 7 in the curing process of concrete. For compressive strength, concrete containing PET resin has lower compressive strength than concrete without PET resin. The difference value is approximately 14% of the compressive strength. At the first and seventh day of the curing process, the compressive strength between the two mixtures *C4* and *C5* still has the difference as shown in Fig. 10. For flexural strength, PET-free concrete has higher flexural strength than PET-free concrete. The difference value is approximately 10% of the compressive strength. Similar to the compressive strength, the flexural strength of *C4* and *C5* composites was different on day 1 and day 7 of curing as shown in Fig. 11. Although the compressive strength and flexural strength of concrete containing PET resin are lower than that of concrete without PET resin. But the difference is not high. Besides, concrete containing PET resin has high formability after printing and does not affect printability. Therefore, PET plastic can completely be applied to concrete 3D printing technology.

VI. CONCLUSIONS

Materials play an extremely important role in concrete 3D printing technology. Experimentally, the study has demonstrated the core properties of materials that affect printability. In which, the formability of the mixture after printing, the plasticity of the mixture are the characteristics that must be paid attention to. Besides, there is the feasibility of using PET resin, coir fiber for concrete 3D printing applications. Concrete 3D printing technology is increasingly developed and applied in the construction industry, so the optimization of printing materials is a problem that must be solved.

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