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3D PRINTED PAVING STONES: A LAB-SCALE RESEARCH

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ABSTRACT

Recent developments lead to changes in the construction industry as well as in many other industries. Three dimensional (3D) printing technology emerges as a new production method that has become popular in the construction industry. Up to date, the manufacturing industry has been utilized 3D printing technology in order to provide automation, production acceleration and waste reduction. However, 3D printing technology is relatively a new concept in the construction industry.

The main methods for producing with 3D printers are (i) additive manufacturing method, (ii) contour work, (iii) concrete printing and (iv) D-shaped process. In addition to the production methods, the mixtures used in 3D printing process also have a significant impact on the production quality. Therefore, design of printable mixture should be investigated carefully.

The main objective of this study is to investigate production process of concrete paving stones using 3D printing technology. However, 3D printers which can print concrete mixtures are rare. Therefore, a 3D printer was designed and built through purchasing of necessary equipment from several suppliers. Suitable concrete mixtures was also be prepared by utilizing construction materials to reach an applicable solution for concrete paving stones. The obtained results present a new method in concrete paving stones production and a 3D printer which is suitable for concrete printing. For the future studies, different materials can be printed through modification of 3D printer and preparation of new mixtures.

Keywords: 3D printer, construction technology, construction industry

1. INTRODUCTION

Recent developments in the world of science and technology have resulted in the emergence and development of new design, fabrication and constriction techniques [1]. Additive manufacturing techniques have gained a solid presence in many areas of industry over the past 30 years [2]. 3D printing (3DP) of concrete structures results in higher precision, safer working conditions, faster construction, and lower cost of construction due to avoiding the costs associated with formwork and labor [3].

The construction industry has traditionally relied on two-dimensional (2D) drawings to convey material properties, performance details and location information. However, with the impact of technological developments on the construction industry, working with 3D models has gained popularity [4]. Another alternative to 3D modeling is the use of advanced 3D solid modeling techniques combined with digital fabrication methods [5]. This method later turned into productions using the 3D printer technique. The 3D printer technique draws attention in the construction industry due to its advantages over traditional manufacturing methods [6-7].

2. LITERATUR REVIEW

In the literature, there are studies examining the mixture designs and mechanical properties of concrete prints made with 3D printers. In addition to this, there are also studies conducted in order to investigate production process of bricks/briquettes from clay and ceramic materials. Moreover, researchers investigate the technical properties of these materials such as strength and thermal insulation [2-8]. However, there is no study in the literature on the mechanical or design properties of the concrete paving stones. Concrete paving stones can be produced in various geometric shapes and have a wide range of applications in terms of 3D printing. As can be seen in the literature review presented in this section, most of the studies on concrete production with 3D printers have been carried out theoretically.

Most of the past studies was conducted on the constructability and mechanical properties of 3D printed concrete. Paul et al. [9] designed a mixing ratio for 3D printing using cement, and the 28-day compressive strength of the produced concrete was measured as 36-57 MPa and the bending strength as 10 MPa. Le et al. [10] developed a high strength fiber reinforced concrete with a compressive strength of 92 MPa and a flexural strength of 11 MPa. Ma et al. [6] used copper waste to develop a printable cementitious mix with good workability and 50 MPa compressive strength. Ting et al. [11] evaluated the effects of material parameters on extrudability and constructability of concrete. Here, material parameters such as glass-binder ratio, fineness modulus and nano-clay content were investigated using the mixture design diagram. Gomaa et al. [12] and Alqenaee and Memari [3] focused on creating a 3D printable, environmentally friendly clay-based mix. As a result, a printable clay-based cob mix design in which the components have sufficient strength for construction was developed, Hojati et al. [13] conducted a study aiming to replace the cement in the mixtures with other cementitious alternatives and to design sustainable mixtures suitable for 3D printing. In the study, the concrete components were designed to be suitable for printing. After that the mixture evaluated in terms of print quality and mechanical performance. Ghanbari-Ghazijahani et al. [1] target to design a material converted into filaments for printing from waste wood and polylactic acid. They tested this material against breaking under three-point bending structurally through 3D printed fourteen composite beams. Overall, they noted promising results for the development of various 3D-printed structural materials.

The number of studies on building materials produced with 3D printers is less than studies examining the design and mechanical properties of mixtures. As mentioned above, studies were generally on the behavior of concrete mixes. In addition, there are studies on building elements or construction materials. Alhumayani et al. [14] compared the environmental impacts of large-scale 3D printer manufacturing according to two different types of construction materials, concrete and cob. In the study, reinforced concrete wall, cob wall, 3D-printed concrete wall and 3D-printed cob wall were compared in terms of environmental effects. As a result, cob wall has the lowest impact on global warming, while concrete wall has the highest impact. However, a concrete wall produced with a 3D printer has 50% less negative impact than a concrete wall. The most important factor here is the use of steel in the traditional concrete wall. Alkhalidi and Hatuqay [15] investigated sustainable, energy efficient and low cost housing production with 3D printers. They focused more on the thermal comfort of the occupants than on the durability of the 3D-printed buildings. As a result, they have presented a guideline adapted to different climatic conditions to create an energy-efficient, comfortable 3D-printed living environment. Tahmasebinia et al. [16] aimed to determine sustainable performance criteria for buildings produced using 3D printers. In this study, minimizing the effect of waste generation was investigated through a model designed in computer environment. According to the results, it was understood that the tensile stresses formed in the recycled high-density polyethylene concrete composite remained within the expected limits. In addition, the geometric composition of the exterior of the structure helps to create passive insulation against heat ingress. Marais et al. [17] tried to measure the thermal performance of 3D-printed lightweight foam concrete and high-performance concrete elements. The results obtained presents that 3D-printed hollow walls tend to perform better when fabricated with materials with higher thermal conductivity. Materials with lower thermal conductivity perform better as void-free walls. Gebhard et al. [18] researched the structural response and crack modeling and kinematics of various reinforcement approaches for 3D printed beams. Consequently, it was observed that the post-tensioned beams broke brittle due to the crushing of the concrete and deformations during bending. Beams with bonded conventional reinforcement, on the other hand, showed multiple bending and shear cracks that allowed the interlayer shear reinforcement to be activated. Zhu et al. [19] experienced the bending behavior of 3D-printed composite beams with different geometric properties. All these beams showed a ductile behavior and provided good shape uniformity. Also, the ultimate bending load of the beams was greatly influenced by the geometric properties. This shows that the structural elements must be adapted to the required geometric properties to obtain the best mechanical performance in terms of compressive strength.

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Most of the current literature in this field focus on printing cement-based concrete. In the past studies, there is no study on the production process of 3D printed concrete paving stones. However, very little research has been done on building materials produced with 3D printers. It is understood that majority the past studies were aimed to investigate concrete mixtures by using different materials. However, studies examining mixtures of clay and mud brick are also substantial. Finally, most of the research on manufacturing with 3D printing has been carried out on a laboratory scale.

This study is the first attempt in researching 3D printing process of concrete paving stones. Moreover, traditional concrete paving stone production will be compared with 3D printed ones. Finally, this study may be beneficial for researcher to investigate different construction materials.

3. MATERIALS AND METHOD

The mechanical part of the 3D concrete paving printer to be manufactured in the study was designed with inspiration from delta FDM printers.

2.1. 3D Printer Mechanical Part

The printer chassis will be formed with 30x30 aluminum sigma profiles (Figure 1). Plastic parts produced from FDM (Melted Filament Production), stainless steel bolts and nuts printers will be used in the connection stage. Flexible plastic elevations will be attached to the printer's feet to prevent mechanical vibration.

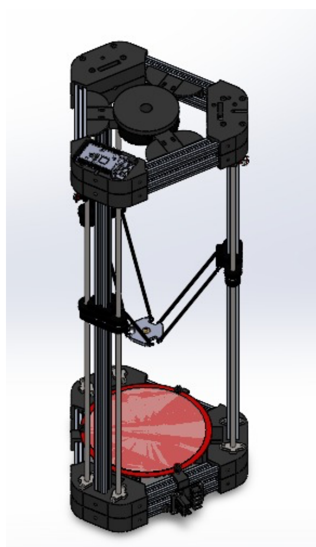

Figure 1

The movement in the axes will be provided by three Nema 17 step motors utilizing the delta arm design. The ground on which the paving stone will be produced will not perform axis movement. Double extruder will be used to make the first contact of cement mortar and chemical during the printing process. Flow settings in each extruder will be made with mechanical and software calibrations. Extrusion materials will be directed to the extrusion stage through hoses from a separate chassis independent of the printer. Cement mortar and accelerating admixture will be extruded using stepper motor and archimedean screws.

2.1.1. Software and calibration

The software of the printer will be implemented with an open-source Marlin software to be suitable for development by third parties. In the calibration phase, open-source computer supported Repetier Host program will be used. Stages such as step settings of the axes, speed, and acceleration will be tested with measuring instruments during the calibration phase and will be processed into the software through the Repetier Host program. As mentioned above, the extrusion flow calculations will be tested until the optimum values are reached during the calibration phase. The optimum values obtained will be transferred to the software.

2.1.2. Security

An emergency button will be placed on the 3d printer to cut the electricity of the system will be in case of any unexpected situation. A fuse will be installed in the power supply to protect the mainboard. The power supply is selected as 12V 15A. In this way, the printer will consume a maximum of 180W per hour.

2.1.3. Production

The. stl (standard triangle language) file format of the paving stone designed during the production phase will be sliced with the open source G-code (program language of CNC machines) generator using simply program and then will be saved to the SD card. Production will be started via the control panel by inserting the SD card into the printer. In addition, G-codes such as speed, extrusion flow rate can be intervened via the control panel.

2.1. Concrete Mixture Design

It is important to obtained satisfactory results from 3D printed concrete paving stones in terms of durability of concrete. The strength variable of cement-based binder building materials is mostly associated with the composite. This shows that the printing quality, writing speed, and adherence between the layers of the concrete mixture will be important. A quick setting of concrete may cause cold joint may be encountered between the layers and the distribution channels of the hydration liquid in the total mass may be blocked. A concrete mixture which sets too slow, may cause collapse of concrete due to the weight of the upper layers. To determine this optimum pressure setting duration, the effects of a standard cement mortar mixture and accelerating admixtures in certain proportions will be measured with an automatic vicat apparatus. Amount and percentage of accelerating admixtures used have an important effect to maintain consistency of concrete mixture through the printing process. Therefore, cement mortar and accelerating admixture will be injected from separate extruders. The addition of the remainder of the chemical that will provide the correct setting time will be during the exit of the cement mortar from the extruder and setting reactions will be initiated on the application surface. Moreover, the pumping speed of accelerating admixture will be calibrated in accordance with the printing speed via software. In this case, it is essential that the cement mortar and the chemical can be pumped separately, and both can be intervened externally. In this study, concrete mortar mixture ratios were designed in accordance with the mixing ratios specified in TS EN 196 1 coded standard. Accordingly, the concrete mortar will consist of 450 gr of cement, 1350 gr of aggregate and 225 gr of water. Finally, 3D printed concrete will have an opportunity to be compared in accordance with related standards.

4. RESULTS AND DISCUSSION

4.1 3D Printed Paving Stones

The most critical stage of the work is the 3D printing of the concrete paving stones. In this stage, concrete paving stones will be produced in accordance to TS 2824 EN 1338, using the designed 3D printer and the prepared mixtures. In this process, it is expected that the mortar can be pumped, shaped, adhered to one another without losing its shape, and set. If it is noticed that a mixture with the desired properties cannot be created, changes will be made in the design of the mixture, and the process will be repeated until the desired concrete paving stones are obtained.

4.2 Performance Tests

It is planned to perform pressure tests in accordance with TS EN 12390-3 to determine the compressive strength of the produced concrete paving stones. The samples of printed concrete will be taken from different sides. Then, 3D printed samples will be tested after curing at 21±2 °C for 28 days... In order to determine the flexural strength, tests will be performed on control samples and 3D printable mortar samples in accordance with TS EN 12390-5. The machines and equipment required to carry out the above-mentioned tests are available in the Construction Materials Laboratory of the Faculty of Engineering of Zonguldak Bülent Ecevit University.

5. CONCLUSION

The main aim of this study was to build a 3D printer to produce 3D printed paving stones in a lab size scale. For this reason, a new concept of 3D printer which can print concrete-based mixtures will be designed. After that concrete paving stones will be produced in several geometric shapes. Finally, mechanic, and economic properties of 3D printed concrete paving stones were analyzed.

Future research will be carried out to find the relation between mixture design, printing behavior and mechanical properties of construction materials for printing. Moreover, possibility of printing different construction materials will be investigated to explore application in the construction industry.

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