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Three-Dimensional, Printable Paving Stone: A Preliminary Study †

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Abstract: Three-dimensional (3D) printing applications have emerged as a new production method in the construction industry. The materials that are to be used in 3D production process play an important role for a sustainable built environment. The main objective of this study is to design a suitable mixture to produce 3D printed concrete paving stones. In this respect, a unique 3D printer was also developed. The results show that the setting time of cement-based mortars was shortened by increasing the ratio of the added accelerator admixture. However, the optimum mixture proportions for 3D printed concrete paving stones were not reached. The results of the study are expected to develop a sustainable method of paving stone production.

Keywords: 3D printer; construction technology; construction material; paving stone

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1. Introduction

Developments and research in technology have resulted in new design, fabrication, and construction techniques in the construction industry [1]. Three-dimensional printing as one of these techniques stands out as it requires minimum human intervention and the minimum pre-processing of raw materials [2]. The 3D printing technique draws attention in the construction industry due to its advantages over traditional manufacturing methods. The major advantages of the 3D printing of concrete are its higher precision, safer working conditions, faster construction, and lower cost of construction, owing to the decrease in costs of formwork and labor [3]. It is also more expeditious than conventional construction methods are, optimizes the site works, enhances the constructability, and reduces the amount of material, and decreases the occurrence of labor-related risks [2].

Three-dimensional printing literature encompasses studies in different industries. However, research on the construction industry on 3D printing technology is relatively scarce. Regarding the current literature, studies examining concrete mixture designs and the mechanical properties of 3D printed concrete exist. There are also studies on the production of bricks/briquettes from clay and ceramic materials. Moreover, researchers have investigated the technical properties of these materials, such as strength and thermal insulation [3–6]. In fact, cementitious materials are more popular than clay-based ones are. Despite the fact that concrete paving stones are one of the most frequently used construction materials, there are no studies in the literature on the mechanical or design properties of 3D printed concrete paving stones. The aim of this study was to design a suitable mixture to produce 3D printed concrete paving stones. To do this, a series of experiments in the construction materials laboratory were conducted.

2. Past Studies

The constructability and mechanical properties of 3D printed concrete can be seen as the most significant issues at the moment. Therefore, many researchers have concentrated on mixture designs or the strength of 3D printed concrete. Paul et al. [7] introduced a

mixing ratio for 3D printing using cement, and the 28 day compressive strength of the produced concrete was measured, 36–57 MPa, and the bending strength was 10 MPa. Le et al. [8] designed a high-strength fiber-reinforced concrete with a compressive strength of 92 MPa and a flexural strength of 11 MPa. Ma et al. [5] utilized copper waste to develop a printable cementitious mix with good workability and 50 MPa compressive strength. Marais et al. [9] measured the thermal performance of 3D printed lightweight foam concrete and high-performance concrete elements. Ting et al. [10] analyzed the effects of the glass-to-binder ratio, fineness modulus, and nano-clay content on the extrudability and constructability of concrete. Gomaa et al. [11] and Alqenaee and Memari [3] developed a printable clay-based cob mix design in which the components have sufficient strength for construction. Hojati et al. [12] investigated ways to replace cement in the mixtures with other cementitious alternatives and to design sustainable mixtures suitable for 3D printing.

Most of the current literature in this field is focused on printing cement-based concrete. They aimed to analyze concrete mixture designs by utilizing different materials. In addition, most of the 3D printing research has been carried out at a laboratory scale. However, there are no studies in the literature on the mechanical or design properties of the 3D printed concrete paving stones. Concrete paving stones are popular around the world [13]. They are widely used in sidewalks, urban roads, etc. The most common grade of concrete paving stones is interlocking pacing stones [14]. Compared with concrete and asphalt pavements, interlocking paving stones offer numerous advantages such as minimal maintenance and economic benefits. Therefore, it can be stated that concrete paving stones deserve enough attention to be produced by utilizing advanced technology. The aim of this study was to develop a new method to produce 3D printed concrete paving stones. As a result, to the best of our knowledge, the present study is the first attempt to design a mixture for 3D printed concrete paving stones.

3. Materials and Methods

3.1. Materials

In this study, cement-based mortar was developed for 3D printed paving stones. The cement-based mortar comprises cement, water, and a set-accelerating admixture. In this process, the pumpability and the stability of the extrusion were considered as the major properties of the cement-based mortar.

The main material used to produce paving stones is CEM I 42.5 N Portland cement, which is in accordance with the standard TS EN 197–1. The water-to-cement ratio was set as 0.4, and Polisan Antiton 100 was used as set accelerating admixture to prevent collapses during the printing process.

3.2. Methods

In this stage, 3D printed concrete paving stones were produced in accordance with TS 2824 EN 1338 [15]. To observe the pumpability and printability characteristics of a cement-based mortar, experiments were carried out in the Construction Materials Laboratory of the Faculty of Engineering of Zonguldak Bulent Ecevit University. The initial and final setting times of the fresh mixture were measured through the Vicat Needle test.

In this study, a new 3D printer was designed and produced (Figure 1). The printer chassis was formed with a 30 × 30 aluminum sigma profile. Plastic parts produced from FDM (fused deposition modeling), stainless steel bolts, and nuts were used. Flexible plastic elevations were attached to the printer's feet to prevent mechanical vibration. The movement in the axes was provided by three Nema 17 step motors utilizing the delta arm design. A double extruder was used to mix cement-based mortar and accelerator admixture during the printing process. Flow settings in each extruder were made using mechanical and software calibrations. Cement-based mortar and accelerating admixture were extruded using a stepper motor and archimedean screws. In the calibration phase, the open source computer supported Repetier Host program was used. Stages such as step settings of the axes, speed, and acceleration were performed through the Repetier Host program. The

stl (standard triangle language) file format of the paving stones was sliced with the open source G-code (program language of CNC machines) generator, and then was saved to the SD card. Production was started via the control panel by inserting the SD card into the printer.

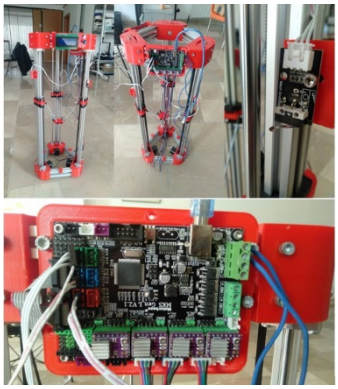

Figure 1. Three-dimensional printer designed for this study.

Three-dimensional printed paving stone samples were cured using a standard water curing protocol. The compressive strengths of the hardened concrete were measured to elucidate the development of its strength over time in accordance with TS EN 12390-3 [16]. After that, they were compared with those for reference paving stones as per the standard TS 2824 EN 1338.

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 Bulent Ecevit University.

4. Results and Discussion

4.1. Cement-Based Mortar Design

Figure 2 gives the results of the setting times of cement-based mortar samples. There are seven samples given in the figure. They were designed through adding accelerator admixture in certain ratios ranging from 0‰ to 3‰ (0:CH00; 5‰:CH05; 10‰:CH10; 15‰:CH15; 20‰:CH; 25‰:CH25; 30‰:CH30). The results show that the setting time of cement-based mortars was shortened by increasing the ratio of the added accelerator admixture. Designing the optimum mixture for the 3D printed concrete paving stones was the aim. In fact, recent findings have some defects and design proportions that should be improved.

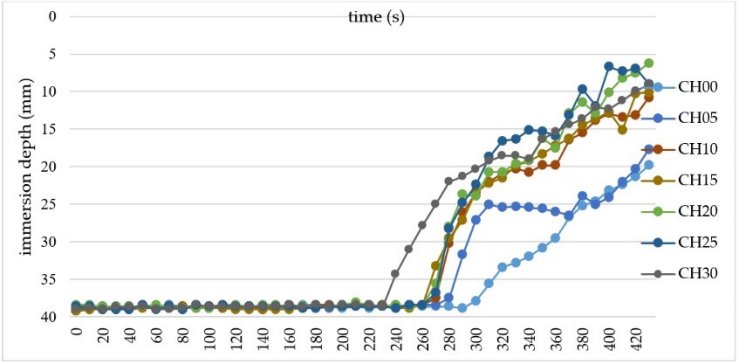

Figure 2. Cement-based mortar setting times.

The print time, setting time, and layer interval time in 3D printing should be considered as the loading increases on newly printed layers [17]. In general, the initial setting

time of cement-based mortars is usually longer than ten hours, and this is not acceptable for the 3D printing abilities of the materials [5]. The printable construction materials should exhibit good workability, an appropriate setting time, and high strength values. The setting time should be kept at 20–80 min, so that the material coagulates rapidly and exhibits high strength values and the desired styling ability within a short time [18]. According to Figure 2, the cement-based mortars designed were insufficient in terms of consistency and quality of printing. Therefore, in the context of the study, more experiments should be conducted to obtain the most suitable mortar design to produce 3D printed concrete paving stones.

4.2. Results of the Compressive Strength Test

The 3D printed paving stones are also required to meet specific mechanical strength parameters in accordance with TS EN 12390-3. The compressive strength of the 3D printed materials was measured 1, 7, and 28 day ages to monitor the strength development over time. To conduct a compressive strength test, the printed samples were placed in the moist cabinet for proper curing. After that, the mechanical properties of hardened 3D printed paving stones were measured according to TS EN 12390-3.

Although the primary findings of the study show promising results to obtain suitable cement-based mortar for 3D printing, the 3D printing process of concrete paving stones was successfully completed. Therefore, the immature results of the compressive strength tests have not been presented in this paper. It should be noted that there is no study which revealed the mechanical properties of 3D printed concrete paving stones. Therefore, the results of the study will be compared to compressive strength of the paving stones produced with conventional construction methods.

5. Conclusions

The goal of this study was to produce 3D printed concrete paving stones. To do this, a unique 3D printer was developed, and a digitally controlled printing process which can build 3D printed paving stones without formwork was designed. As soon as the suitable cement-based mortar was obtained, the 3D printed paving stones were produced. Thereafter, the mechanical results of compressive strength tests were published. Three-dimensional printing could be used instead of a conventional production machines to achieve real, rapid manufacturing. Further research will be conducted to assess the structural behavior of 3D printed construction materials under the provided conditions to improve the mechanical and architectural properties of these materials.

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