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Extrudability of Mortars Designed for 3D Printers

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Self: The use of 3D printers in the construction industry is becoming more widespread day by day. Mortars used in 3D printers must be specially designed in order to be printed. In this study, the extrudability of mortars designed for 3D printers was investigated. Mortars using cement as a binder were prepared with aggregates with a maximum grain size of 0.4 mm and water/cement ratios of 0.33, 0.35, 0.37. The mortars were extruded in the extrusion device at speed ranges of 50-200 mm/min and using circular and rectangular outlet tips. In the study, RAM type extrusion was used. The length of the mortars to flow uninterruptedly after exiting the extrusion device was measured. According to the results obtained, as the extrusion speed increased, the mortars were able to flow uninterruptedly. On the other hand, mortars extruded with a rectangular outlet tip, which has a larger cross-sectional area, were obtained in a more continuous manner than those extruded with circular tips. For 3D printed mortars, mortars that can be extruded continuously and do not disperse on the surface on which they are applied have been obtained.

Keywords:3D printer, mortar, extrusion.

Extrudability of Mortars Designed for 3D Printers

Abstract: The use of 3D printers in the construction industry is increasing day by day. The grout used in 3D printers must be specially designed to be printed. In this study, the extrudability of mortars designed for 3D printing was investigated. Mortars using cement as binder were prepared with aggregates with a maximum particle size of 0.4 mm and at a water / cement ratio of 0.37. The mortars were extruded in the extruder at speeds of 50-200 mm / min using a circular and rectangular outlet. RAM type extrusion was used in the study. The continuous flow length of the mortars after exiting the extruder was measured. According to the results, with the increase of the extrusion speed, the continuous flow of the mortars was achieved. On the other hand, mortars extruded with a rectangular exit end could be obtained more seamlessly than those extruded with circular ends. For 3D printer mortars, mortars that can be extruded continuously and do not disperse on the surface were obtained.

Keywords:3D Printer, mortar, extrusion.

1. Introduction

The desire to build buildings in less time, with less manpower, at low cost, and to be environmentally friendly and energy efficient has led to the search for different production techniques. The latest technology in these production techniques is 3D printing printers. 3D printing printers, which have achieved many positive developments in the industrial field, have also added a new dimension to the construction industry [1]. New additive manufacturing methods for cementitious materials have high potential to increase automation in the construction industry. However, these methods are subject to specific characteristics of the manufacturing process.

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It requires the development of new materials that meet performance requirements [2]. Appropriate characterization methods of these materials are currently being investigated by many researchers [3]. One of these methods is the printing of mortars by extrusion method. Extrusion mortars have begun to be used as printing mortars in three-dimensional printers in today's technology. The most important features of these mortars are that they exhibit thixotropic behavior after pressure and continue to maintain this behavior under the upper layers [4]. Additive Manufacturing (EM), especially in the construction industry, also known as 3D printing, can be defined as a manufacturing technology that manufactures structures by adding materials in a controlled manner, usually on a layer-by-layer basis [5]. In general, the additive manufacturing method, which produces an object directly by the digital design method and is applied with robotic technology-based equipment, today uses materials such as polymers [6], foams [7], glass [8], timber [9] and steel as filaments. In construction technology, these filaments are replaced by mortar or concrete [10].

Recently, 3D printing has become one of the most popular additive manufacturing technologies. Today, many components are produced with this technology for various applications such as fashion, food, automotive, medical and construction [11]. In recent years, automation has also become increasingly common in the construction field [12]. Extrusion printing is the most successful method for printing cement-based materials, but still faces significant challenges such as pumpability of materials, constructability, consistency in materials, flowability, and processability. Many studies are being carried out to overcome these difficulties. The extrusion printing technique consists of an extruder extruding cementitious slurry through a nozzle attached to a frame to print a layered structure. The first studies of this technique in the field of construction were made by Le et al. It was started to be made by [13].

Shakor et al. [14] carried out a number of tests to investigate the printable and mechanical properties of cementitious 3D mortar mixture proportions. The study investigates the properties of 3D printed fiber reinforced cementitious mortar prisms and elements in conjunction with automation to achieve optimum mechanical properties of 3D printed mortar and to achieve suitable fluidity and consistent workability for mixed cementitious mortar during the printing process.

Buswell et al. [4] mentioned different extrusion nozzles used in circular, oval and rectangular shapes, but they did not give much detail for the differences between the nozzles. It has been noted that it is necessary to have a suitable nozzle to achieve the highest possible layer and the required shape. They argued that the circular nozzle provides more convenience to change the nozzle angle when printing the mortar [15]. In the study conducted by Kwon [16], it was concluded that the square-shaped nozzle had a better surface quality than the ellipse type. Lim et al. [17] used circular nozzles with diameters of 4–22 mm, and as a result of their studies, they concluded that the optimum nozzle diameter was 9 mm.

However, the evaluation of fresh mortar workability properties has generally been based on flow properties [15]. Additionally, an exact processability criterion for printability has not yet been determined. The design of printable mortars differs from conventional concretes. The requirements for 3D mortars are not limited to the hardened properties of the mortar. Extrudability and shape retention requirements must also be met in these mortars. In other words, it must be malleable enough to pass through the pressure system without using excessive pressure and without ruptures and/or voids during the flow of the mortar from the extrusion. Another issue is that after printing, it should be able to carry the layers on top of it as much as possible and the number of layers should be increased as much as desired [18]. The underlying layers must be able to maintain their stability without deformation. Therefore, when both requirements are met, the grout can be considered printable. Tay et al. [19] designed mortars for 3D printers with different components and determined both the printable properties of these mortars, the number of layers and the workability of the mortar in the printed form, and the spread values of the same mortars on the spreading table (Figure 1). In order to have the best consistency for 3D printable mortar, the spread value should be between 130-210 mm.

It is recommended to take it. While the number of layers can be increased in some mortar designs, it has been stated that interruptions and gaps occur in the printing of these mortars. Therefore, it is necessary that the designed mortars not only lie on top of each other, but also be able to be printed without interruption. There are few studies on this subject in the literature.

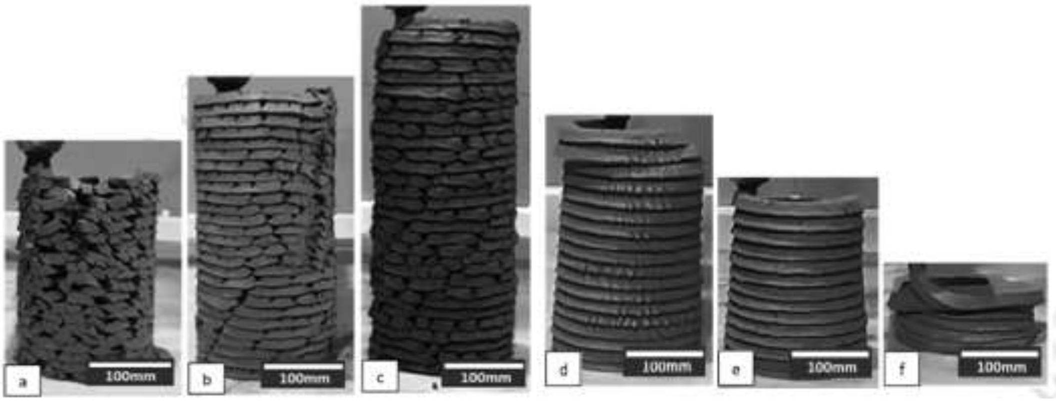

Figure 1. Number of layers of 3D printer extruded mortars (a: 20; b: 27; c: 30; d: 18; e: 13; f: 6) [19]

On the extrudability of mortars, Figueiredo et al. [20] also conducted some studies. A total of 12 different mortar designs were made in the study, and the use of polyvinyl alcohol (PVA) fibers was also tried. Three of these designs were obtained as both printable and pumpable to a distance of 5 m. While most of the designed mixtures showed breaking behavior when initially extruded, when PVA fiber was added to these mixtures, they could be extruded without breaking. Therefore, mortars have a suitable processability and their extrudability comes to the fore so that they can be printed on 3D printers. In line with the information given above, this study aims to investigate the extrudability of mortars at different printing speeds, unlike the studies given in the literature, so that the overlapping layers in the 3D printing mortar design can carry more layers without deformation.

2. Experimental Studies

2.1. Used materials

Experimental studies were carried out on mortars, and CEM I 42.5 Portland cement, which complies with the TS EN 197-1 [21] standard, was used as the binder. Specific surface area of cement is 3320 cm2/g and its specific gravity is 3.1. The chemical properties of cement are presented in Table 1.

Table 1. Chemical components of cement

Component, %	CaO	SiO_2	Get_2HE_3	Fe_2HE_3	MgO	Na_2ARROW_2HE		SO_3	KK
Cement	63.6	19.6	4.72	3.27	1.91	0.34	1.06	4.72	2.69

Silica sand in the range of 0.5-400 microns was used as aggregate in mortar production. The specific gravity of sand is also 2.64. Again, city tap water was used to create the mortar.

2.2. Mortar Productions

For mortar design and extrudability for 3D printers, cement, sand and water were mixed as components and mortar was obtained. Mortars at water-cement ratios of 0.33, 0.35 and 0.37

have been prepared. When the components are used by weight above 0 for each determined water-cement ratio, the mortars are mixed until they become homogeneous in the extract container.

The aggregate:cement ratios and the amount of aggregate are n of this ratio (aggregate, cement, water) Figure 2).

Figure 2. A view from the preparation of mortars

2.3. Experiments carried out

After the mortar mixtures were made, the spreading properties of the mortars were determined on the spreading table for the purpose of workability control. For this purpose, the mortars are placed in a mini cone, which is a part of the spreading table (Figure 3.a). After the cone was pulled upwards, the mortar was hit by 15 strokes through the arm under the table, and with this shaking it was ensured that it spread on the table. The spreading diameters of the spread mortar in the perpendicular direction were measured and their arithmetic average was taken (Figure 3.b).

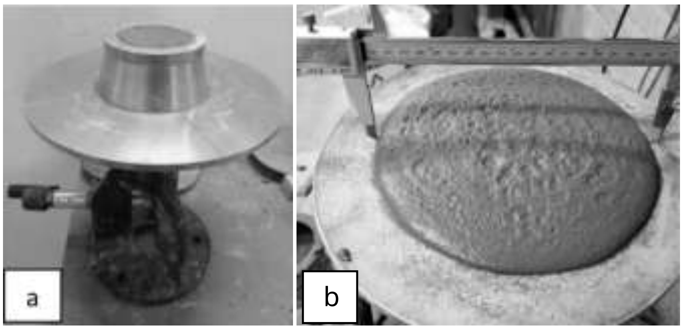

Figure 3. a) Appearance of the mortar on the spreading table; b) diameter measurement on spreading mortar

After the spreading experiment, extrudability experiments were carried out. In this context, emphasis was placed on the design of mortars of suitable consistency that can flow in the extrusion device (Figure 4) without clogging or breaking. RAM type extrusion was used as the extrusion device. After the prepared mortar was placed in the chamber of the device, a pushing force was applied to the mortar with the piston at six different speed values between 50-300 mm/min, and it was aimed to flow continuously from the smaller diameter outlet (Figure 4). The chamber outlet end of the device is 400 mm above the ground. The length at which the mortar could flow downwards without breaking after leaving the nozzle was measured and recorded with a meter during the flow. The nozzle size, which is the exit tip, is a circular long tip with a diameter of 10 mm and a length of 40 mm; A rectangular long tip with a cross section of 10x15 mm and a length of 40 mm was used. In addition, in order to see the effect of the exit tip, a total of 4 different nozzle shapes were tested on the device in experimental studies, using short ends of the same sections (circular and rectangular) with a length of 10 mm (Figure 5).

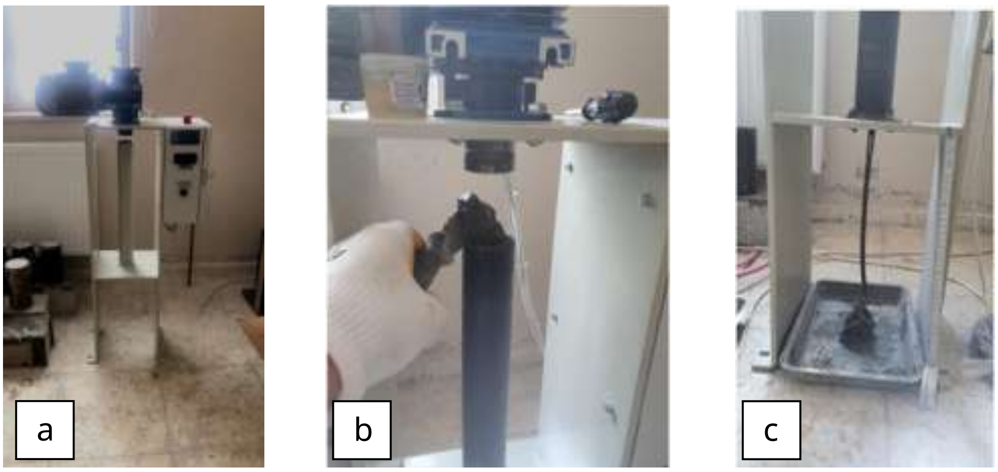

Figure 4. Extrusion unit designed and built within the scope of the project
(a: Extrusion device; b: device chamber; c: mortar flow)

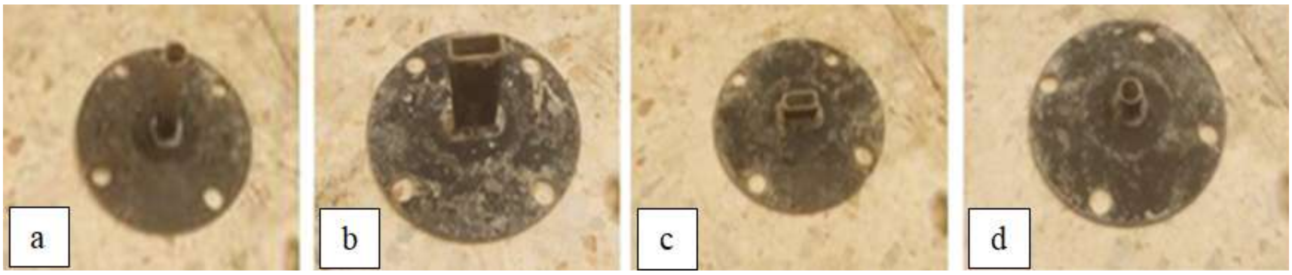

Figure 5. Nozzle shapes used in the extrusion of mortars (a: circular long; b: rectangular long; c: circular short; c: rectangular short)

Within the scope of experimental studies, 72 different mortar data were recorded, including three different water-cement ratios, 6 different speed values and 4 different nozzle shapes. For each water-cement value, the visible viscosity values of the mortars were measured with a Brookfield DV-II model Viscometer device at 75-200 rpm shear rate values, depending on the capacity of the device. Viscosity measurements were made at laboratory ambient temperature using a wing-shaped tip numbered V-72.

3. Experimental Results

After each mortar was prepared, it was subjected to an impact spreading test on the spreading table and the average of the resulting spreading diameters is given in Figure 6, depending on the water-cement (w-c) ratio. While the spreading value of the mortar with the lowest w-c ratio was 140 mm, the spread of 165 mm and 180 mm was obtained in the mortars with 0.35 and 0.37 w-c values, respectively. As the amount of water in the mortar composition increased, the internal friction between the aggregate and cement particles decreased and the workability of the mortar increased, resulting in higher spreading values on the spreading table. When compared with the literature in terms of spread values, Tay et al. It is seen that it falls within the spread values recommended by [19] for 3D printing without breakage.

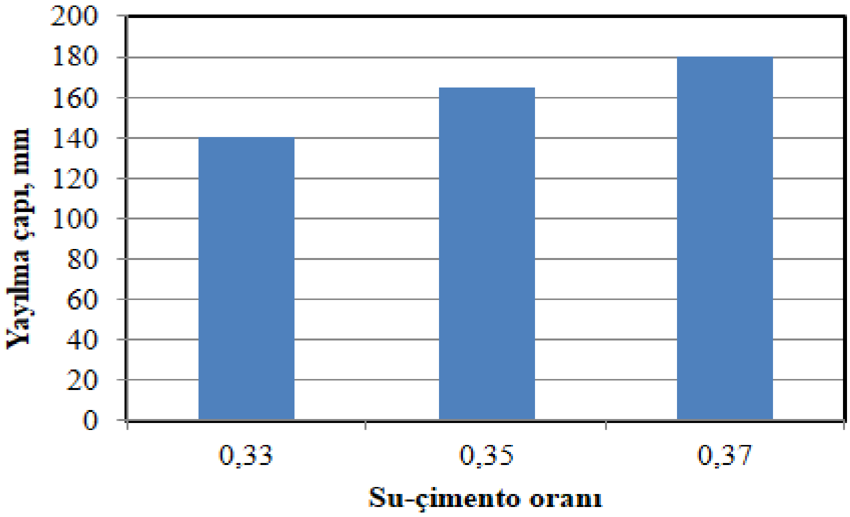

Figure 6. Spreading values of mortars

When a long circular outlet tip is used as the nozzle shape in the extrusion device, the flow length of the mortars depending on the speed values is seen in Figure 7. As mentioned before, since the height of the chamber outlet end from the ground is 400 mm, the target values were for the mortars to flow at this length. As the extrusion speed values increased, the flow length of the mortars at all w-c ratios also increased steadily. Mortars extruded at low speed values flowed intermittently. If the speed was low during extrudability, the mortar was pushed slowly during pressure, and the mortar that started to flow was able to break and flow at certain distances due to the effect of the unit weight and gravity. These breaking distances, in other words flow lengths, were obtained higher with the 0.33 s-ç ratio compared to mortars with other s-ç ratios. Mortars with all w-c ratios were able to flow continuously without breaking at an extrusion speed of 300 mm/min.

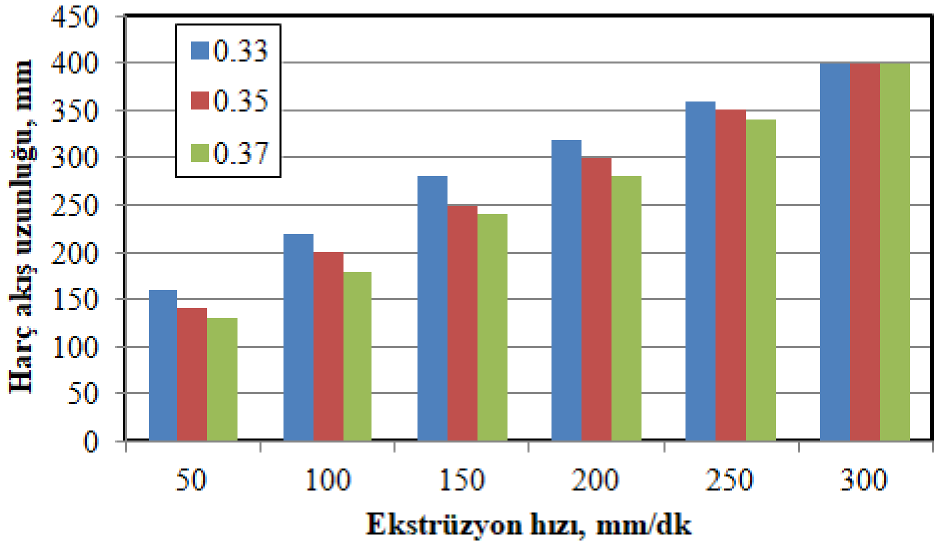

Figure 7. Extrudability of mortars from circular long end

When a rectangular long tip was used as a nozzle, increases in flow lengths were obtained by increasing the velocity values, as in the circular long tip (Figure 8). However, as a different situation, by using the s-ç ratio of 0.35 and above, the flow length of the mortars at extrusion speed values

It is seen to be significantly less than the 0.33 s-c ratios. In addition, it is seen that two mortars can flow uninterruptedly at a speed of 300 mm/min, and mortars with a w/c ratio of 0.37 can flow for a length of 340 mm. Another point is that longer flows were obtained compared to mortars using a circular cross-section tip with the same exit length. This is because the exit cross-sectional area is larger than the circular tip. However, as the w-c ratio increased, the workability of the mortar increased and the cohesion, which is the internal gravitational force, decreased, causing the mortar to break more easily during flow [20]. Therefore, it is seen that the cohesion properties of the mortars to be designed can be determined by extrusion testing. Images of continuous flow of mortar from long ends with both circular and rectangular cross-sections are given in Figure 9.

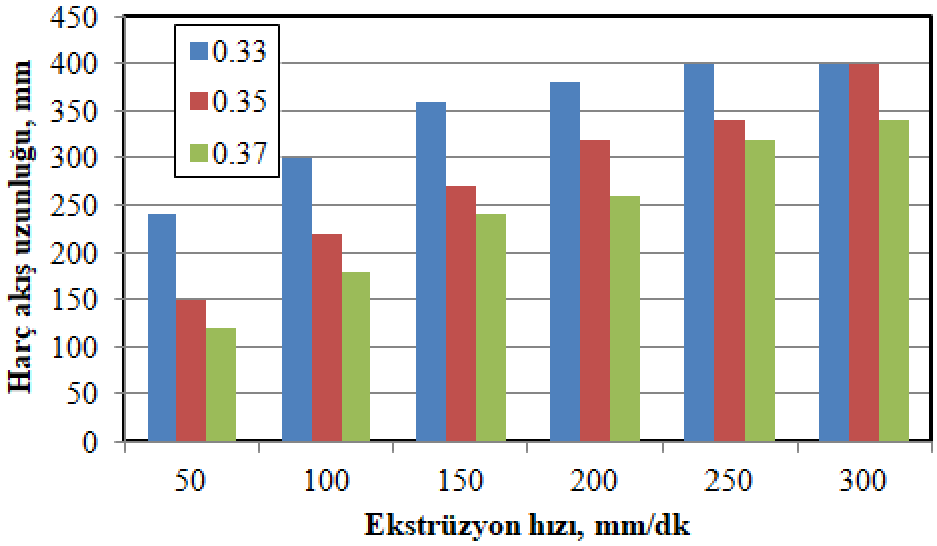

Figure 8. Extrudability of mortars from the rectangular long end

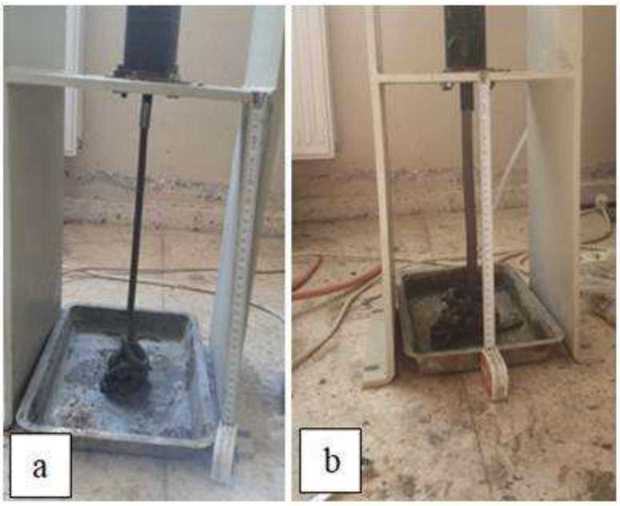

Figure 9. A view of the mortars extruded without breaking (w-d: 0.33)
(a: long circular tip; b: long rectangular tip)

If a short outlet end was used in the extrusion device, lower mortar flow lengths were obtained compared to the flow values obtained at long ends with the same cross-sectional area (Figure 10 and Figure 11). In short tip nozzles, relatively shorter flow lengths are obtained compared to other long tips, as the mortar moves through the shorter nozzle and is directly exposed to downward gravity. When the increase in cross-sectional area is added to this situation, it is clearly seen from the graphics that lower flow lengths are obtained in rectangular short ends than in circular short ends.

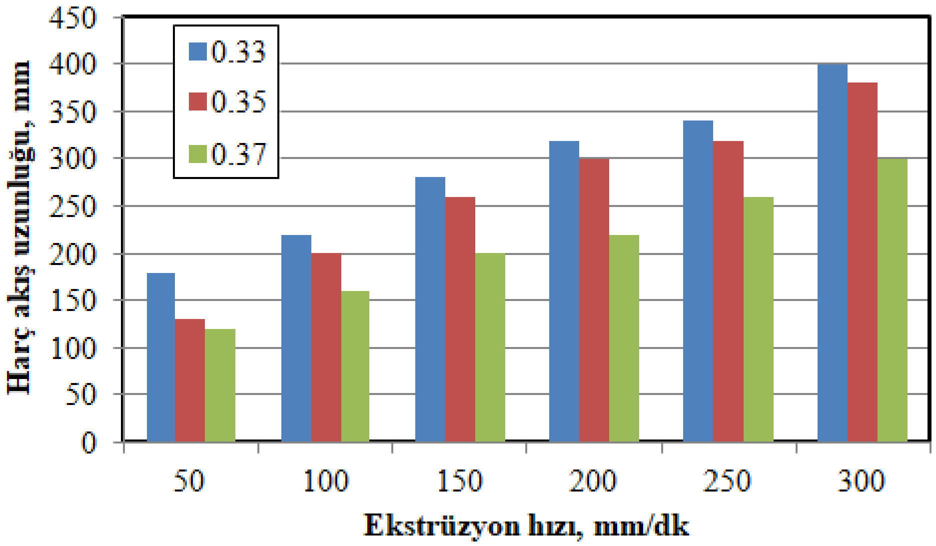

Figure 10. Extrudability of mortars from circular short end

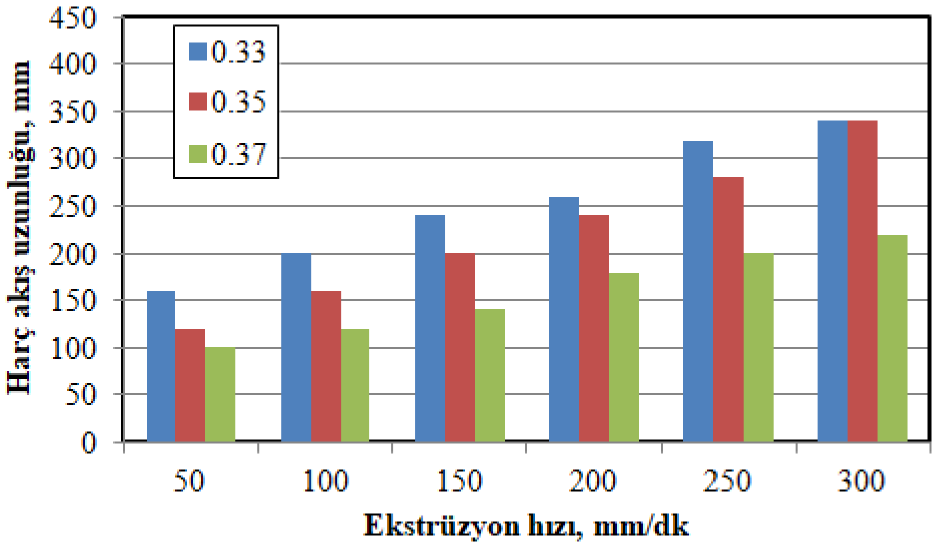

Figure 11. Extrudability of mortars from rectangular short end

The apparent viscosities of the mortars at different deformation rates for each w-c ratio are given in Figure 12. While close values are obtained at low w-c ratios (0.33 and 0.35) for all deformation rates, it is seen that lower viscosity values are obtained with the w-c ratio of 0.37 due to the decrease in internal friction between the particles of the mortar. As the deformation rate increased, the viscosity values of all mortars decreased due to increasing shear stresses. Since the maximum flow lengths in the extrusion device are achieved at high extrusion speeds, it can be recommended that the viscosity values of the mortars around 200 rpm generally remain between 100-200 cp. It can be seen that a significant flow length of over 350 mm is achieved at these speed values, especially for long circular and rectangular tips.

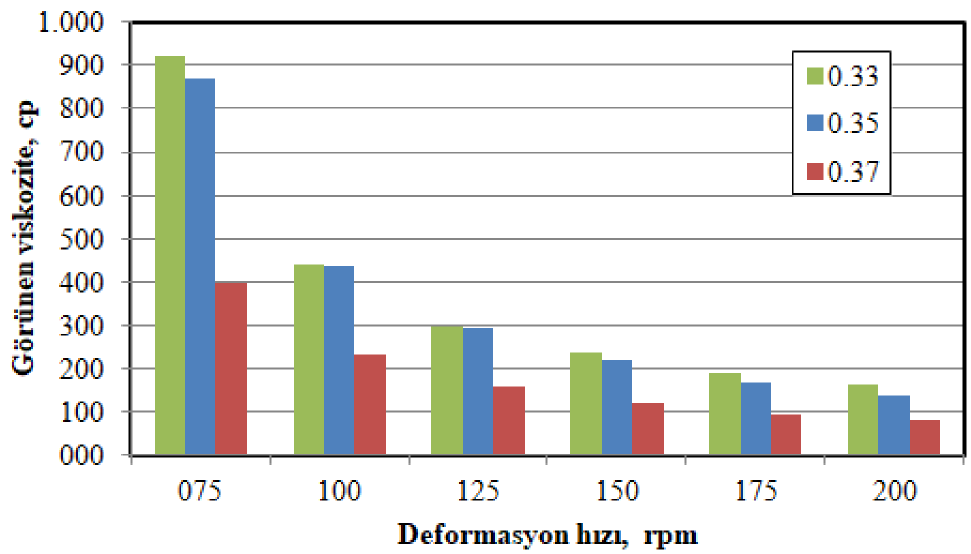

Figure 12. Apparent viscosities of mortars

4. Results

In this study, the ability of mortars prepared at different w-c ratios by extrusion method from different types of nozzles for cement-based 3D mortar printers to flow without breaking was investigated and the findings are summarized below.

- When the w-c ratio of the mortars was increased, more workability was achieved in the spreading table due to the decrease in the internal friction effect.
- When the extrusion speed was increased, the flow lengths of all mortars increased noticeably, regardless of the outlet end.
- Since the cross-sectional area at long rectangular ends is greater than at circular ends, more uninterrupted mortar flows can be achieved. However, at the shorter ends, longer mortar flows were measured at the circular ones.
- Especially at the short ends, the flow lengths of the mortars in both circular and rectangular end types took lower values than the long end types.
- While the w/c ratio of the mortars was low, due to the high cohesion, continuous flow could be achieved without breaking at a distance of 400 mm at high extrusion speeds, even under the influence of gravity. As the w-c ratio increased, the continuous flow of the mortars began to disappear.

As a result, for 3D printers, it is necessary to produce mortars with a low water-cement ratio as much as possible, in order to have both suitable processability and high cohesion, and to avoid deformation under the overlying layers after printing. In this way, the mortar will be printed without interruption or breakage during flow, and the deformation problem in the lower layers will be minimized.

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