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Modeling a rheological cement mixture suitable for 3D printing technology with Fuzzy Logic

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Abstract
The material preferred in additive manufacturing technology 3D printing, which has advanced in current years and has been utilized in the construction sector, is a cement-based mixture. Considering the experimental studies for this mixture, which does not have a definite formulation, the success of the resulting products shows the rheological properties that enable the material to be built. Data on the constructability of the material can be obtained by defining the volume ratios of the resulting samples with the Fuzzy Logic method. For the constructability of the material, a Mamdani type fuzzy model was created and the "CENTROID center of gravity" method was stipulated as the clarification method. While the component material ratios of the cementitious mixture create the fuzzy inputs of the system, static and dynamic yield stresses are reached as fuzzy output values. 15 rules obtained from experimental studies that enable the system to work were defined and then the operation of the method was tested. In this study, it is aimed to develop a decision mechanism for intermediate values that are not encountered in the experimental results by blurring the mixture models supported with definite findings.

Keywords
Cement, Fuzzy Logic, Rheology, 3D printing.

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1. Introduction

The use of 3D printing, which is one of the technological innovations, is accepted as a preferred production method with an extensive sort of materials and in different fields.

Additive Manufacturing (AM) is the general name of production technologies in which materials are deposited in layers and 3D objects are produced. With this technology, ceramic, metal, polymer, composite, etc. can be obtained from three-dimensional (3D) model data. Parts with complex geometries can be produced using a large number of materials. Today, different names such as "Rapid Prototyping", "3D Printing", "Indirect Additive Manufacturing" are used for Additive Manufacturing Method. It has been modeled by melt stacking (FDM), three-dimensional printer (3DP), selective laser sintering (SLS), selective laser according to material type, and joining technique, which was first developed by Charles Hull in the 1980s under the name Stereolithography (SLA).

The general advantages of the additive manufacturing method over traditional techniques are high precision production of parts with complex geometry, customization of production, less material wastage, flexibility in design, and short production time in a small number of productions. Combining the layers of part production in this method allows sensitive and controlled production, which is not possible with traditional production methods (Harun et al., 2018). The ability to produce parts directly from the CAD model without using molds in additive manufacturing techniques provides significant advantages in terms of cost and production time in the production of parts designed and modified according to the person/desired specifications (Kim, Lin, & Tseng, 2018). Unlike traditional processing methods, manufacturing by combining powder, filament and resin and reusing unused material minimizes material waste (Srinivas and Babu, 2017). Since there is no need for a separate model for each part with different geometry in additive manufacturing, it has design flexibility in part production. Parts with different geometries can be produced directly on the 3D printer in one go, significantly reducing production time and cost.

The initial 3D printer was designed in 1984, and 3D printing has become one of the fastest printers in the last decade. This emerging technology was initially very complex and expensive. Over the years, 3D printing has begun to exist in everyday life and printers have begun to be widely used in all kinds of industries (such as bio-engineering, aviation, electronics, textiles) .

The advantages of AM, also called as 3D printing, are the reason it attracts much attention in various industries, including construction. Some of these advantages include high efficiency, cost effectiveness, great efficacy, saving of labor and high design choice (Chua & Leong, 2014). The initial effort to utilize cement-based materials in the additive manufacturing approach was proposed by Pegna (1997). There are currently three large-scale additive manufacturing processes targeting construction and architecture in the public sphere: Contour Crafting (Khoshnevis, Hwang, Yao, & Yeh, 2006), D-Shape (Monolite) (Lim et al., 2012) and Concrete Printing (Lim et al., 2009). All three have proven successful manufacturing of substantial size components and are appropriate for applications in the architectural area.

AM and digital manufacturing fetch novel perspectives to cement based material and concrete structure. The option of constructing reinforced concrete structures without formwork is a great benefit due to reducing costs; formwork accounts for 35-60% of the total rough cost in reinforced concrete structures (Arnaud Perrot, Rangeard, & Pierre, 2016). In addition, 3D printing technology allows the replacement of human labor with robots that are digitally controlled, and it will also be possible to produce in conditions that are not suitable for human work with the development of these new techniques.

3D printing technologies are considered an environmentally friendly option and offer almost unlimited possibilities for complex geometric forms, compared to building structures with traditional techniques, although creating 3D printed structures is still a new practice in the construction field. There is no need for any mold, additional protective insulation or paint in the structure during printing. With these features, 3D printing technology not only saves material but also reduces waste generation. All kinds of plastic forms can be printed in 3D printing technology, but it is very important that the material maintains its fluidity while it remains in the printing machine, and that the form hardens as it is printed and hardens without losing its shape. After the 3D printing machine prints, it prepares the ground for the next layer (Banfill and Swift, 2004). Among the rheological properties of the material, the static yield strength and dynamic yield strength determine the quality of the structure that comes out of 3D printing.

Experimental study by Liu, Li, Weng, Wong, and Tan (2019) 3D printable cement-based material mix samples content contains five sets of mixtures, sieved sand, ordinary portland cement (OPC, ASTM type, Class 42.5), fly ash (FA, Class F), silica fume (SF, undensified, Class 940, Elkem company) and water. In each experiment, 6 g of superplasticizer (SP, MasterPozzolith-R168 from BASF) was used to decrease water consumption (Weng, Li, Tan, & Qian, 2018). The ratios of the 3D printable cement-based material, prepared with 22 different test samples, with an optimum static and dynamic yield stress were determined by printing with a printing machine (Liu et al., 2019).

Necessary experiments and optimum values for 3D cementitious material printing were determined, but since there is no single optimum value or a single mixture model, Fuzzy Logic method was used to analyze whether the mixture is printable.

Another study in which Fuzzy Logic method is used in the AM process is the risk assessment of 3D production in terms of scope, timing, cost and quality. For this purpose, the result of a survey study evaluated by experts and academicians in the sector was evaluated with the Fuzzy logic method (Moreno-Cabezali & Fernandez-Crehuet, 2020).

The fuzzy logic method is one of the artificial intelligence systems that do not have clear truths but establish a thought generation system such as problem solving, searching, and heuristic programming in line with appropriate parametric data. By using this method, it is aimed to create intermediate values and probabilities from the mixing ratios of 3D printable cement materials whose calculations are precise. Data are obtained that are determined by experiments and mathematical formulas and as a result reveal certain rheological properties and material behaviors. By recording these data with the fuzzy logic method, rules were created to activate the method, and values that were not determined experimentally were determined.

While producing new cement-containing materials that can be printed with 3D technology, it is aimed to develop a fuzzy logic model associated with the control mechanism. With this investigation, it is intended to develop a technique that includes experiments and mathematical formulas of the material formed and in addition to this, proposes material composition by fuzzy logic method to intermediate calculation values.

2. Aim of the study

3D cementitious material printing, which is one of the developing technology products, is a construction method that is still under development and although it does not have a clear formulation, materials with suitable content can be reached as a result of various experiments and observations. There are many kinds of 3D production methods and the materials and tools used in each method differ.

The quality of the concrete used in 3D printing depends on the material ratios it contains. For this reason, the ideal printable cement ratios are defined as input in the fuzzy logic system in order to obtain the same quality print in case the mixing ratios change. The yield stresses that determine the stability of the material are the output function. Experimental studies are scientific methods in which definite data are obtained as a result of long preparation processes, performing the experiment, observation and reporting.

Therefore, they are reliable data sources. The aim of this study is to show that precise and accurate information can be output in a very short time as a result of processing previous experimental data in Fuzzy Logic with an accurate and sufficient number of rule bases, instead of many factors such as time, cost, equipment, and providing a suitable environment for the experiment.

3. Use of 3D printing technologies in construction

In layered manufacturing technology (Contour Crafting), layers of concrete, mortar or cement paste are sprayed and located via a portal or robotic arm operated. The concrete must remain in place immediately after spraying and develop sufficient strength to consolidate the layers placed on it. The difference from slipforming in terms of the physical processing properties of concrete in layered spraying is that the concrete is immobile from the moment of spraying and immediately supports itself. Slide molding is immobile and self-supporting from the casting time while exiting the mold. Nevertheless, slipforming is a gravity-driven process, while layered spraying is a pressure-operated spraying process. While allowing shape freedom in layered spraying, slide mold technology is advantageous against the possibility of adding reinforcement from the open top of the mold (Reiter, Wangler, Roussel, & Flatt, 2018).

Industrially, layered spraying is a robust construction technique that can be improved. To attain this goal and enhance the process, two main restraints must be overwhelmed. The first limitation is that a weakness in the structure can occur during bonding between printed layers. It is significant to remind that the bonding strength amid layers decreases over time (Le et al., 2012). The second constraint is to monitor material strengthening in the passing period: The material must be hard enough to bear the weight of later deposits. This restriction may lead to an increase in production time (Arnaud Perrot et al., 2016).

The juxtaposition of these two constraints turns the process into a paradox about the rate of production. The time interval amid the binary deposited layers should be lengthy enough to offer sufficient mechanical strength to maintain weight. Therefore, the optimized time interval between the layers needs to be produced in the shortest time that permits the stability of the structure throughout construction.

During the layered construction of a wall, the first deposited layer is subjected to the heaviest load. The yield stress should be sufficient to ensure wall stability during operation. Here, the paste should be sufficiently fluid for spraying, but robust enough for the mechanical stability of the structure. One way to circumvent this paradox is to set the correct composition of the cement-containing material to warrant both adequate fluidity through spraying and stability afterwards set (Arnoud Perrot et al., 2012).

The cement-based material that can be utilized in 3D cementitious material printing technology must be pumpable in semi-solid semi-liquid form in fresh state and its rheological properties must have appropriate qualifications. For cementitious materials that require special application, such as self-compacting cement, the dynamic yield stress should be of high viscosity and low enough to hold the material. Arnaud Perrot et al. (2016), although constructibility is comparative to the static yield stress, the geometry factor significantly affects the constructability by increasing the static of the material.

In layered production, the yield stress in each layer during spraying should be at least 150 Pa to support the typical 1 cm layer height and prevent flow. For each top layer, the yield stress must be greater, taking into account the weight of additional layers to prevent it from flowing out of the lower layers. Setting time should be waited before the layers deteriorate and continue with fresh material. In layered spraying, compositions that offer elevated yield stress (thixotropy) or contain viscosity modifying mixtures are frequently utilized. Since thixotropic build-up in these materials can be reversed by pumping, it is convenient to use because it eliminates the problems associated with beginning and ending the process action and provides a reproducible yield stress. Nevertheless, the strength increment is restricted and confines building heights (Reiter et al., 2018).

According to Weng et al. (2018) previous studies, the geometry factor of the hollow cylinder was examined and it was proven that the short constructability printing time for structures with low slenderness has a positive effect on the static yield stress. Because of this positive relationship, static yield stress was decided as one of the output parameters in Fuzzy Logic method to distinguish the constructability of 3D printable fresh cement based material. Also, Weng et al. (2018) the pumpability of cement based material is very important for 3D cementitious material printing and is contrariwise proportional to dynamic yield stress. While maintaining good constructability to advance the pumpability of the cementitious material, the dynamic yield stress must be as low as conceivable. In the fuzzy model based on this study, another output parameter that determines the modeling of the suitability of the cementitious material's properties is dynamic yield stress.

3.1. Literature study

There are many studies investigating the effects of high viscosity compressible cement components on the material and the rheological properties of the cement mixture.

According to the study of Chen and Kwan (2012) to improve the rheology, strength and packing density of the paste, superfine cement is utilized and the added water in a cement paste should be at a sufficient level as it fills the spaces between solid particles. Since unfilled holes can become air pockets, meaningfully reducing the strength. In the printable cementitious material tests, the ideal water measure was determined as 33% and the water and silica fume rates were kept constant while the other component ratios were changed.

In a review article reported by Jiao et al. (2017), they examined the effect of components on the rheological properties of fresh concrete, many articles were examined and according to the result of this, it was determined that fly ash (FA) had a convenient linking with rheological possessions. In the largest cases, the material yield stress and plastic viscosity upsurge with the addition of the FA content. The fineness of FA or particle size distribution also pointedly affects machinability. In this work, the particle size of the FA was kept constant and the effects on the rheological properties of the cementitious material were recorded by changing the rate of fly ash in the mixture. Accordingly, the increase of FA increases the dynamic yield stress and decreases the static yield stress.

The lubricating effect significant for pumping cementitious material can be enhanced by adding silica fume (SF). Two studies have been conducted on the thixotropic behavior of self-compacting concrete. The first of these was done by Assaad et al (2003), while the other was by Rahman et al (2014). It has been stated that the plastic viscosity and yield stress upsurge with the increment of silica fume. Conversely, Ahari, Erdem, and Ramyar (2015) have reported that silica fume drops plastic viscosity while increasing yield stress in the study titled thixotropy and structural deterioration properties of concrete in cementitious materials. There may be two reasons for the difference: first, the SF in the mixtures to vary in the surface properties of the material; secondly, the interaction of SF and other components in the mixture and the reflection of this interaction on the rheological properties (Jiao et al., 2017). Looking at the studies on silica fume, it was observed that silica fume increased yield stress in all studies. In this study, the ideal SF in the cement mixture is fixed at a rate of 4%.

According to Liu et al. (2019) the influence of cementitious material mixtures on rheological properties is fairly multifaceted when the components of the material vary. Therefore, when investigating the effects of 3D cementitious material printing on the rheological properties of mixtures, it is essential to comprehend the interaction amid the components that make up the mixture.

Because of the changeability of cementitious material properties, the mixture can be obtained with various components and it is necessary to design appropriate tests to determine the effects of the composition on rheological properties. Often a group of tests must take place by deliberately varying the material proportions. This corresponds to 3 control levels for each mixture component in engineering terms, and $3^5 = 243$ tests for 5 components in this study. In the previous literature, Liu et al. (2019) has decided to keep the water and SF rate constant as a result of achieving the ideal values in the mixing tests. In this way, the number of components affecting the mixture has been reduced to three variable components: Ordinary Portland Cement (OPC), sand and fly ash (FA).

Liu et al. (2019) made use of DoE (Design of Experiments), which is a commercial mixture design algorithm. With this scientific approach, the program proposes an optimal number of experiments and reduces long and costly processes.

4. Research method

In the study, after the literature review, 3D printing techniques were examined, and the experiments on the printable cement material were investigated. 15 rules have been defined in line with the experiments examined and the data obtained by recording the ideal compressible cement ratios. In accordance with the rules defined by the fuzzy logic method, material volume ratios inputs that could not be obtained through experiments and static and dynamic yield stress result values from rheological properties were obtained. While applying the fuzzy logic method, a Mamdani type fuzzy model was created in the MATLAB Fuzzy Toolbox program and the “CENTROID” method was proposed as the defuzzier method. The “View Rules” command of the program was used, and the working percentage of the rules was tested by comparing numerical data with graphic data.

4.1. Fuzzy Logic

Fuzzy logic theory, which was put forward by the scientist Zadeh in 1965, is a multiple logic system that can also evaluate indeterminate things similar to human thinking. Binary logic, which is the approach of classical logic called Aristotelian logic to events; that is, unlike the ‘yes-no’ system, it evaluates the solution not as 0 or 1, but as a range of 0-1 (Zadeh, 1965). Fuzzy logic can also be called an expanded version of classical logic. In classical logic, a suggestion is right or wrong, but in real life, there is no right or wrong solution in uncertain situations that are frequently encountered. Fuzzy logic can produce solutions in information systems that can think like a human, make decisions, make choices, and use initiative in such situations (Kahraman & Pakdamar, 2019).

The rubrics and limits in the numerous papers and codes proposed are demarcated by strict boundaries, that is, sharply. Approaches in the structural system, modeling and numerical analysis, make the correctness of these restrictions debatable (Pakdamar & Güler, 2012).

Some of the main features of fuzzy logic are as follows (Kubat, 2013):

- Complete reasoning in fuzzy logic can be observed as a limited case of approximation.
- The whole thing has a degree of importance in fuzzy logic.
- In fuzzy logic, information can be inferred as a flexible or fuzzy constriction sum over the sum of variables.
- Inference can be seen as a progression of propagation of flexible constrictions.
- Any logical system can be fuzzified. Two important features of fuzzy systems are that they provide well performance for specific claims.
- Fuzzy systems are well suited for ambiguous or rough inference, and particularly for systems whose model cannot be mathematically established.

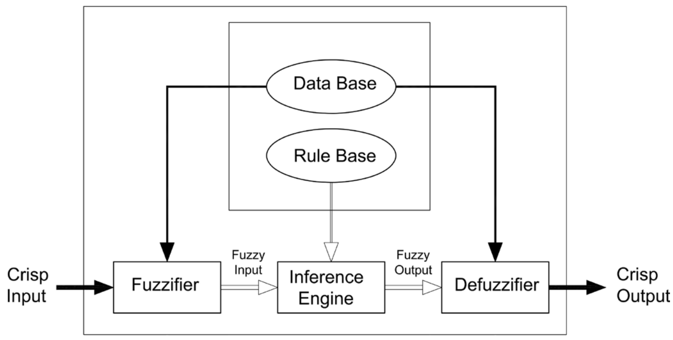


Figure 1. *Schematic representation of a fuzzy logic system.*

Research shows that the Fuzzy Logic method is used in various sectors. Some of them, along with the classical questionnaire to understand the social justice behaviors of administrators in educational institutions, were applied on the same sample and fuzzy results were found to be more accurate and sensitive (Şahin et al., 2021). It has been observed that when the fuzzy method is used in the evaluation of architectural design studio studies, an inference can be made that deals with subjective and objective situations together (Authors, 2019). In addition to training studies, various scenarios have been produced in order to increase customer satisfaction in warehouse management of companies and lower and upper limits have been determined. It has been concluded that the results obtained in the fuzzy simulation are reasonable (Tokat et al., 2021).

When the studies in the field of construction are examined, it is seen that "fuzzy controllers" are used to optimize comfort conditions such as ventilation, lighting and heating of smart buildings, so the efficiency of the equipment can vary according to both outdoor conditions and user requirements (Wahid et al., 2019; Mofidi and Akbari, 2020). In addition, there are many studies in the literature in which the cement strength is estimated by the Fuzzy Logic method. Akkurt et al. reported that a fuzzy logic estimation model was created for the 28-day compressive strength of cement mortar under standard curing conditions, and it proved to be a model that can be used by researchers and engineers by obtaining successful results (2004). On the other hand, Beycioglu et al. showed that the mechanical properties of cements blended at high temperatures were compared with the fuzzy logic model and statistical data, and accurate information flow was obtained from the fuzzy logic system, except for minor deviations (2017). In the study of Gülbandilar, the effects of FA and SF on the setting time of OPC were estimated using fuzzy logic. The model created with fuzzy logic gave initial set time values similar to those obtained from the experiments (2013).

In his study, Moreno-Cabezali proposed a fuzzy logic-based model based on the risks in the literature in AM R&D projects, which is one of the 3D printing methods (2020). However, no study has been found showing that this method is used for a new technology product, which is printable cement.

The development of computer integrated information system, raises the development of software for the concrete mix design. These systems are expected to greatly affect construction design over the past decade and have revolutionary effects on future consumption of natural resources and building material designs (Boukhatem, Kenai, Tagnit-Hamou, & Ghrici, 2011).

The operation of a fuzzy system in general is given in Figure 1, in fuzzy systems, first of all, the strictly expressed input and output parameters of the problem are determined. Second, the fuzzification process is carried out. Fuzzification process is to define a membership function (MF) to input parameters. Third, the logical relationships between fuzzy input and output parameters are determined with IF-THEN clauses to form a rule base. Rule base determination can be verbal or quantitative in the form of existing knowledge, empirical knowledge, observation, experience or prediction. Fuzzy logic is a flexible system in which all of these data types can be modeled and transferred to digital environment. The created fuzzy rule base is applied to the model and the fuzzy inference system becomes operational. Result data are obtained as fuzzy. In order to be understandable in machine language, sharp (Aristotle) output data is obtained by applying deffuzzier system.

This article uses the method of fuzzy experiments with logical results to create an efficient material composition in the performance evaluation of 3D printable building systems.

5. Analysis of the experimental datas

As a result of the experiments designed with the DoE algorithm to produce a 3D cementitious material with printable properties, Liu et al. (2019) determined 22 cement mix ratios. In the DoE mix design, the rheological properties of the materials responded to the input variables (volume ratios of materials).

Material rheology is significantly affected by mixing time, mixing and temperature values depending on the rotational speed. For this reason, the same mixing was done for all experimental groups in order to preserve the rheological properties. The specimen volume utilized for apiece testing was kept constant and mixed with the same model mixer. The resulting mixture, dynamic and static yield stresses were measured with a rheometer and the resulting values were calculated. The fresh rheological properties of the cement-based material can be calculated based upon the equation (Heirman, Vandewalle, Van Gemert, & Wallevik, 2008).

The formulas that can be used to calculate the static and dynamic yield stress are as follows.

$$T=[(4\pi h \ln(Ro/Ri))/(1/Ri^2-1/Ro^2)]\tau_0 + [2\pi^2 h/15(1/Ri^2-1/Ro^2)]K.N \quad (1)$$

$$\tau_s=T_{max}/2\pi Ri^2 h \quad (2)$$

- τ_d is dynamic yield stress;
- τ_s is static yield stress;
- T is the torque value (Nm) measured in the inner cylinder of the rheometer;
- N is the rotational speed (rpm) of the outer roller;
- h is the height of the liquid in the viscometer;
- K is consistency coefficient;
- Ri is external radius of the inner cylinder;
- Ro is internal radius of the outer cylinder.

In the experiments, the weight parameters of the static yield stress and dynamic yield stress obtained in the test results were determined in order to achieve the goals. In this investigation, static yield stress is much more significant through optimization. Considering the pumpability and constructability factors, the weight parameter of static yield stress was determined as 0.7, and the weight parameter of dynamic yield stress was described as 0.3. In order to obtain these values, the optimal volume ratios of the five components (cement, sand, fly ash, water and silica fume) are 0.148, 0.221, 0.261, 0.33 and 0.04, correspondingly. Considering the 22 cement mix volume ratios designed with the DoE algorithm, it is seen that no mixture evaluation is at the optimum level. For this reason, the 23rd mixture ratios in Table 1 are specified as the optimum mixture (Liu et al., 2019).

Table 1. *Volume ratios and fresh rheological properties of the designed cementitious materials.*

INPUTS						OUTPUTS	
No	Cement (%)	Sand (%)	Fly Ash (%)	Water (%)	Silica Fume (%)	Static Yield Stress(Pa)	Dynamic Yield Stress (Pa)
1	0.16	0.21	0.28	0.33	0.02	2363.13	244.81
2	0.12	0.23	0.30	0.33	0.02	913.88	153.16
3	0.12	0.21	0.30	0.35	0.02	517.19	70.53
4	0.12	0.24	0.25	0.35	0.04	576.91	124.41
5	0.12	0.21	0.28	0.35	0.04	962.93	149.90
6	0.16	0.21	0.26	0.35	0.02	672.88	98.26
7	0.14	0.226	0.266	0.34	0.029	1237.27	211
8	0.16	0.24	0.25	0.33	0.02	1346.46	187.22
9	0.16	0.21	0.25	0.34	0.04	3057.11	322.23
10	0.14	0.21	0.30	0.33	0.02	572.11	256.26
11	0.12	0.26	0.225	0.35	0.02	969.86	126.55
12	0.16	0.21	0.26	0.33	0.04	5952.11	248.16
13	0.12	0.26	0.25	0.33	0.04	1687.37	208.80
14	0.16	0.22	0.25	0.33	0.04	5392.64	274.12
15	0.16	0.21	0.25	0.35	0.03	965.60	154.09
16	0.14	0.26	0.25	0.33	0.02	540.65	94.07
17	0.12	0.21	0.30	0.33	0.04	3373.43	271.33
18	0.12	0.26	0.27	0.33	0.02	497.46	72.67
19	0.16	0.22	0.25	0.35	0.02	526.25	95.19
20	0.15	0.21	0.25	0.35	0.04	1775.26	226.39
21	0.14	0.226	0.266	0.339	0.029	1082.26	168.61
22	0.14	0.226	0.266	0.339	0.029	1117.42	179.49
23	0.148	0.221	0.261	0.33	0.04	4880	201

The aim of the optimization is to create high static yield stress, so it was considered to contain the lowermost water level and uppermost level of silica fume. When the water content and silica fume content were fixed at 0.33 and 0.04, correspondingly, the responses (static yield stress and dynamic yield stress), cement, sand volume ratios were re-evaluated. Thus, the number of variable compounds in the mixture has been reduced to three. Mixture samples no. 12, 13, 14 and 17 in Table 1 are ideal in terms of water and silica fume ratios. The sample rates no. 23 were determined as optimum and the input and output values of these samples were processed as a rule in the fuzzy logic method.

5.1. Modeling data with Fuzzy Logic

Liu et al. (2019) and earlier Weng et al. (2018), cementitious mixture components were determined as OPC, sand, FA, water and SF, and many studies were conducted to determine the appropriate volume ratios. The volume levels of water and SF were fixed as 0.33 and 0.04, and it was calculated that values close to the ideal static yield stress were obtained, and then the number of variable components was reduced to three.

In MATLAB Fuzzy Toolbox program, the five components of the cementitious mixture are defined as inputs with fixed values of water and SF, OPC, sand and FA with variable values. The mixing ratios in the study are expressed in percentile and it is necessary to obtain a value of 1.0 (100%) from the sum of the components. As output, static and dynamic yield stress values are defined from the rheological reactions of the mixture. In Table 2, low, ideal and high input and output ranges are determined as evaluation criteria for each data.

The ranges of values specified in Table 2 were found by Liu et al. (2019) has been determined in accordance with the data obtained from the experimental mixture designs and other literature researches.

While defining the rules that make the system work, it is necessary to define 3^3 = 27 rules in theory because three variable inputs have three different criteria. However, it has been observed that some rules do not apply to ensure that the total volume ratio of components is 1.0 (100%). For example, if OPC is high, sand is high, FA is high; The sum of the input values of the rule followed by will be greater than 1.0 and the rule will remain undefined. For

Table 2. *Value ranges of inputs and outputs defined in the proposed fuzzy model.*

INPUTS						OUTPUTS	
Value	Cement (%)	Sand (%)	Fly Ash (%)	Water (%)	Silica Fume(%)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)
Low	0.12-0.15	0.20-0.22	0.22-0.26	0.30-0.33	0.02-0.04	500-4880	70-200
Ideal	0.15	0.22	0.26	0.33	0.04	4880	200
High	0.15-0.18	0.22-0.26	0.26-0.30	0.33-0.36	0.04-0.06	4880-7120	200-350

Table 3. *Rules for defining the system in Fuzzy Modeling.*

No	Rules
1	IF cement is high, sand is low, fly ash is high, THEN static yield stress is high, dynamic yield stress is high.
2	IF cement is high, sand is ideal, fly ash is low, THEN the static yield stress is ideal and the dynamic yield stress is high.
3	IF cement is high, sand is low, fly ash is low, THEN static yield stress is low and dynamic yield stress is high.
4	IF cement is high, sand is low, fly ash is ideal, THEN static yield stress is high and dynamic yield stress is high.
5	IF cement is high, sand is high, fly ash is low, THEN static yield stress is high and dynamic yield stress is low.
6	IF cement is ideal, sand is ideal, fly ash is ideal, THEN static yield stress is ideal and dynamic yield stress is ideal.
7	IF cement is ideal, sand is high, fly ash is low, THEN static yield stress is ideal and dynamic yield stress is ideal.
8	IF cement is ideal, sand is low and fly ash is high, THEN static yield stress is high and dynamic yield stress is high.
9	IF cement is low, sand is low, fly ash is high, THEN static yield stress is low and dynamic yield stress is high.
10	IF cement is low, sand is ideal, fly ash is high, THEN static yield stress is low and dynamic yield stress is ideal.
11	IF cement is low, sand is high, fly ash is high, THEN static yield stress is low and dynamic yield stress is ideal.
12	IF cement is low, sand is high, fly ash is ideal, THEN static yield stress is low and dynamic yield stress is ideal.
13	IF cement is low, sand is high, fly ash is low, THEN static yield stress is low and dynamic yield stress is ideal.
14	IF cement is low, sand is low, fly ash is low, THEN static yield stress is low and dynamic yield stress is low.
15	IF cement is high, sand is high, fly ash is high, THEN static yield stress is high and dynamic yield stress is high.

this reason, 13 rules have been entered into the system as defined in Table 3, in addition to these rules, if all input functions are low, the output functions will be low, and if they are high, the output functions will be high. Thus, 15 rules have been defined.

5.2. Fuzzy findings

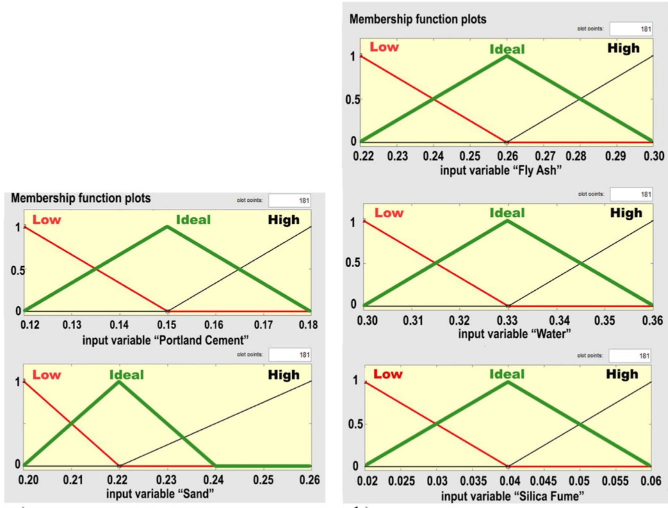
The volumetric values of the components affecting the 3D cementitious mixture and the rules obtained from the experiments were recorded in the Fuzzy Logic system with IF-THEN expressions. The recorded MF input values are shown in Figure 2a and 2b, and output values are shown in Figure 3.

Input value ranges according to the data obtained from experimental studies and consisting of cementitious material components from MFs;

- OPC: It is in the range of 0.22-0.30 and the ideal value is 0.26,
- Sand: It is in the range of 0.20-0.26 and the ideal value is 0.22,
- FA: It is in the range of 0.22-0.30, the ideal value is 0.26,
- Water: It is in the range of 0.30-0.36 and fixed at 0.33, which is the ideal value according to the test results,
- SF: It is in the range of 0.02-0.06 and recorded to be constant at 0.04, which is the ideal value according to the test results.
- Value ranges of output functions that respond to input functions;
- Dynamic Yield Stress: According to the experimental data limited in the 100-350 Pa strength value range, the ideal value is 200 Pa,
- Static Yield Stress: It is limited to the strength range of 1000-7000 Pa and according to experimental data, the ideal value was recorded as 4880 Pa.

In order to test the functioning of the system in the Fuzzy Logic model, the value ranges specified in the rules were compared visually on the Matlab Rule Viewer panel. The 6th rule is "IF OPC is ideal (0.15), sand is ideal (0.22), FA is ideal (0.26), water is ideal (0.33), SF is ideal THEN static yield stress is ideal (4880 Pa), dynamic yield stress is ideal (200 Pa). " It has been defined as the optimum value (Figure 4).

The 9th rule is "IF OPC is low (0.12), sand is low (0.20), FA is high (0.30).



a) b)

Figure 2. (a) Portland cement and sand input membership functions; (b) Fly ash, water and silica fume input membership functions.

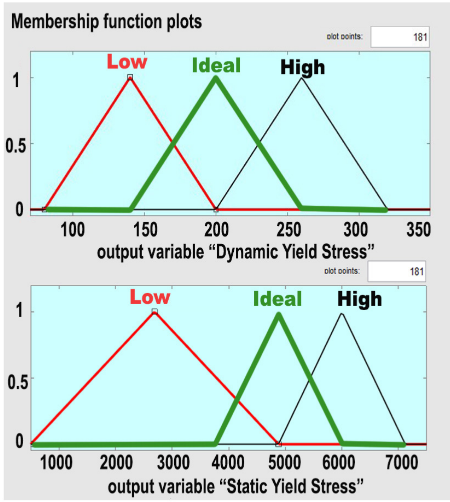


Figure 3. Static and dynamic yield stress output membership functions.

THEN static yield stress is low, dynamic yield stress is high." As stated in the rule, the static yield stress of the output parameters yielded results in the low value group (2690 Pa) and the dynamic yield stress in the high value group (260 Pa) (Figure 5). It is seen that the rule that becomes active according to the given values is the 9th rule.

The 12th rule is "IF OPC is low (0.12), sand is high (0.26), FA is ideal (0.25). THEN static yield stress is low (2690 Pa), dynamic yield stress is ideal (200 Pa)." As stated in the rule, the static yield stress of the output parameters resulted in the low value group and the dynamic yield stress in the ideal value group (Figure 6). The FA value is at a low value close to ideal, therefore the percentile of the output values has

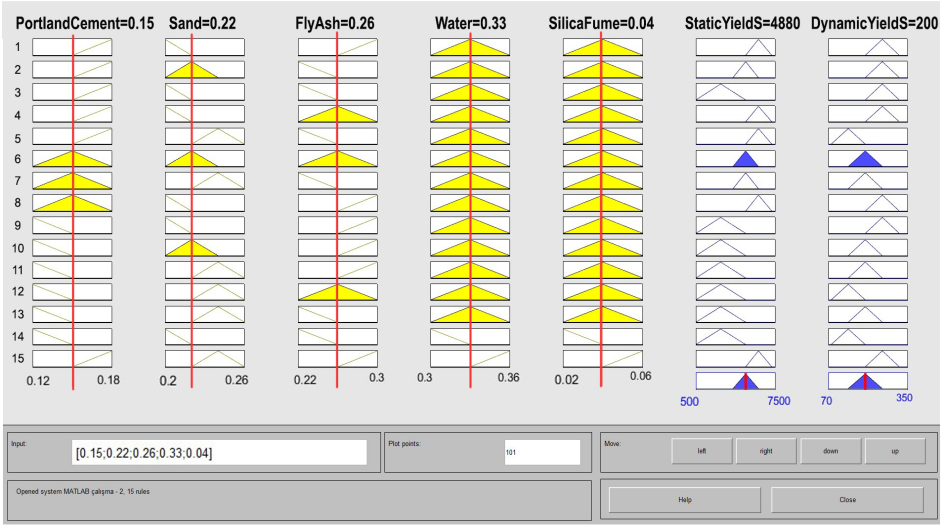


Figure 4. *Rule 6 with the expression that IF all input values are ideal, THEN the output values are also ideal, which indicates the optimum value.*

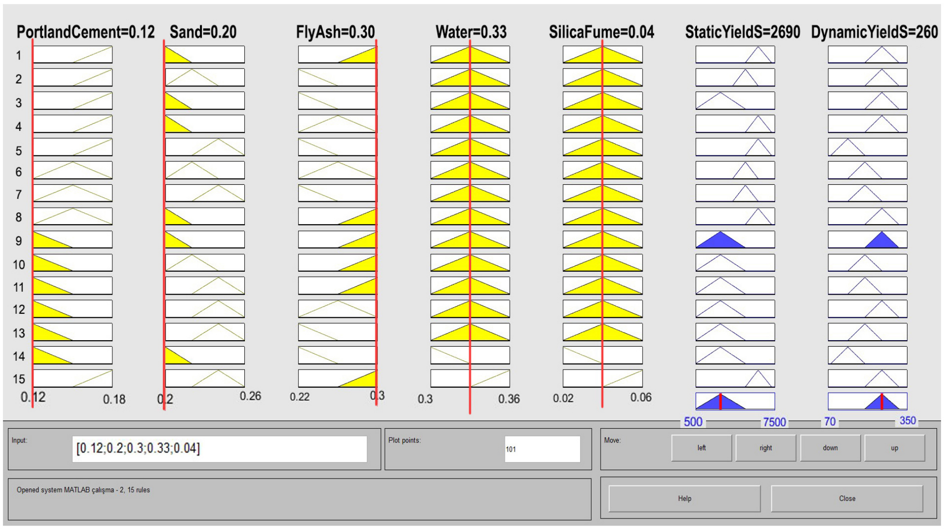


Figure 5. *Fuzzy output values where cement and sand are low and fly ash high, Rule 9.*

decreased. Output values will be displayed at the highest level if FA is exactly at its ideal value.

The 14th rule is "IF OPC is low (0.12), sand is low (0.20), FA is low (0.22). THEN, static yield stress is low (2690 Pa), dynamic yield stress is low (140 Pa)." As stated in the rule, the static yield stress of the output parameters resulted in the low value group and the dynamic yield stress in the low value group (Figure 7).

The 15th rule is "IF OPC is high (0.12), sand is high (0.26), FA is high (0.25). THEN static yield stress is high (6000 Pa), dynamic yield stress is high (260 Pa)." As stated in the rule, the static yield stress of the output parameters resulted in the low value group and the dynamic yield stress in the low value group.

In the Fuzzy Logic method, when the output values in the membership function should be low, the maximum defined value is 2690 Pa for static yield stress and 140 Pa for dynamic yield stress. When the output value should be high, the maximum defined value is 6000 Pa for static yield stress and 260 Pa for dynamic yield stress. It has been determined that the system works in accordance with the rules. In order for the value ranges to be wider and more detailed, the defined functions should be diversified with expressions such as lowest, low, ideal, high, and the rules should be more clear and comprehensive.

6. Conclusion and evaluation

Required mixture values and rheological reactions for 3D cementitious material printing modeled with fuzzy logic. It is compatible with the experimental

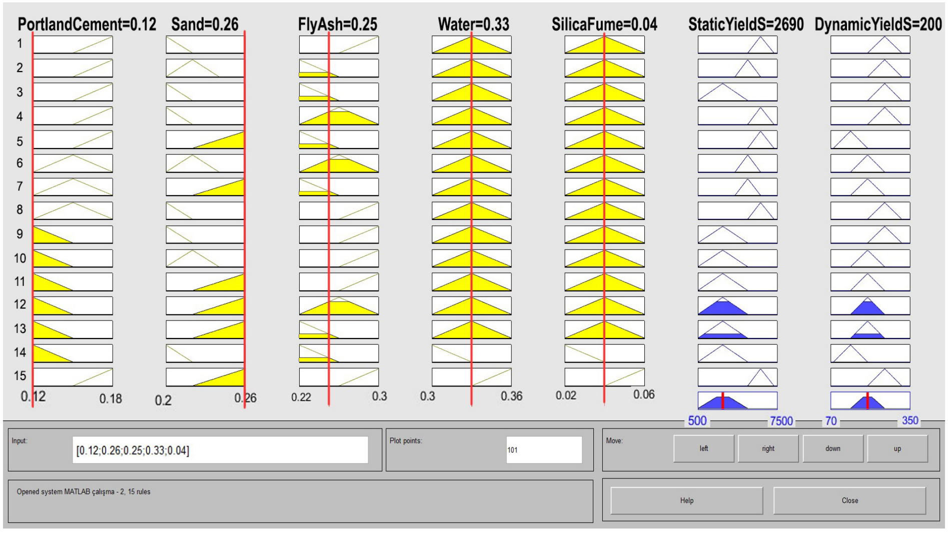


Figure 6. *Fuzzy output values where cement is low, sand is high, fly ash is low value Rule 12.*

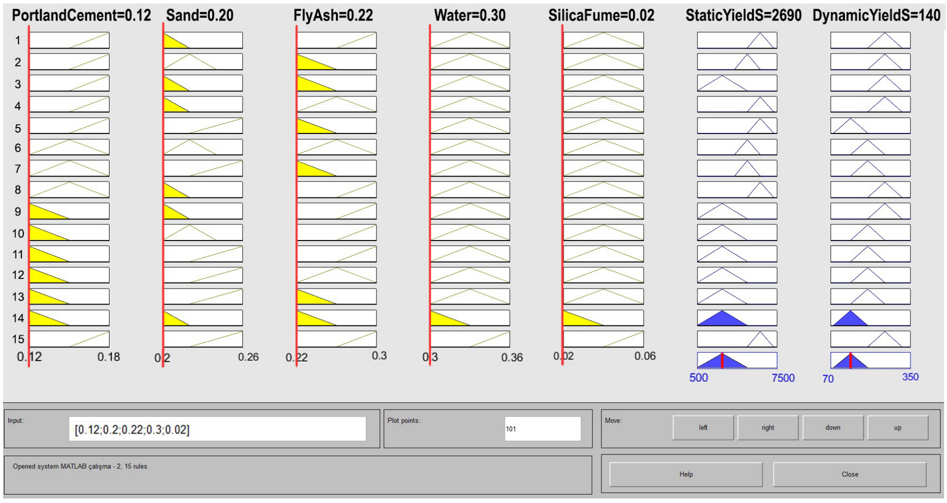


Figure 7. *IF all inputs are of low value, THEN all outputs are also of low value, Rule 14.*

results of Liu et al. (2019) and the study data support each other. In this way, while the dynamic and static yield stresses of the cementitious material ratios are obtained as output, it can be easily understood whether the material is suitable for printing.

In fuzzy matlab application, triangular fuzzy MF is used for inputs and outputs. As the number of these triangular fuzzy MFs increases, more precise results can be obtained. Researchers can also use other MFs (trapezoidal fuzzy membership function, Gaussian fuzzy MF, etc.) suitable for their problems. In addition, centroid defuzzification function was used with Mamdani method in Fuzzy Matlab. Researchers can use other defuzzification functions (bisector, mom, lom, etc.) or the Sugeno method as appropriate to their problem.

3D printing technology is a digital production system. For this reason, it can work integrated with many digital data analysis systems such as Fuzzy Logic. The Fuzzy Logic method has features and advantages that can be improved by using it in the 3D construction industry:

- Experimental studies have been carried out to increase the quality and environmental properties of 3D printable cement, as it is a developing construction system (Liu et al., 2019; Nething, 2020; Souza et al., 2020; Kruger, 2019). In line with the data obtained from these studies, fuzzy inferences can be made according to the properties expected from the material and the optimization of the material can be achieved.
- Fuzzy Logic method can determine the most suitable mixture for the continuation of the process in case

of a decrease in the printable cement mixture input rates used at the construction site.
- When data input is provided to the system regarding the environmental impact of the printable cement mixture ratios, it can provide environmentally friendly material information.

With this study, it has been shown that it is possible for the machines to decide the adequacy and suitability of the material in line with the data recorded by the Fuzzy Logic method to the technology of making unmanned construction by printing 3D cementitious material. The study is limited to be effective when the main materials show variable properties in the printable cement model containing OPC, sand, FA and SF. However, the ratios of mineral additives affecting the material can also be included in the fuzzy method. If this control mechanism is developed, the material components can be brought together in accordance with the desired properties. Thus, it has been revealed that performance levels can be bendable by utilizing fixed optimum values depending upon the mixing ratios of the cementitious material composition.

Fuzzy Logic material evaluation is an easy-to-understand system that can be applied to many products such as self-compacting concrete and bio-based concrete, as well as on 3D printable cement. This study is intended to deliver a basis for possible upcoming investigations.

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