Workability Analysis of 3D Printing Materials for Applications in The Construction Industry

Ridho Bayuaji[1], Hendro Nurhadi[2], Beta Rahayuning Pratiwi[1], Yuyun Tajunnisa[1]*

***Abstract*— The development of 3D Printing machine technology as a printing tool that uses an additive manufacturing method system with the aim of producing a three-dimensional (3D) object or object according to the default digital design file. 3D Printing was created to facilitate construction work, with 3D Printing construction work becoming lighter because this tool saves time, and costs, and reduces the risk of work accidents. With 3D Printing, work runs quickly and avoids problems in the development process. In the last few decades, many developed countries have used 3D Printing technology in making buildings. The 3D printing process basically consists of three different stages namely, data preparation, material preparation and transfer to the printer, and the printing stage. In the data preparation stage, the components are designed as 3D CAD models, then converted to STL (Stereolithography) format and sliced with the desired layer depth. The preparation of concrete involves mixing and placing it into a container. Once fresh concrete has been placed into the container, it can be channeled smoothly through a pump-pipe-nozzle system to print self-compacting concrete filaments, which build structural components layer by layer. The material used in this 3D printing method was Portland cement where this cement is easy to find among the public. Portland cement itself is the cement that is commonly used as a basic material for making concrete, plaster, mortar, and non-specialized mortar. In addition, fly ash and silica fumes are also added as a mixture. The addition of silica fumes increases the compressive strength of concrete. Furthermore, the addition of fly ash to the concrete has the effect of reducing drying shrinkage; but reducing the compressive strength of the concrete. In this study, the author focuses on the workability of 3D Printing concrete materials, and the impact of the material was added with additional type C fly ash and silica fume, namely flowability. The result is a concrete mix design that has good flowability value to be applied to the 3D Printing method.**

***Keywords*—3D printing, Construction, Fly ash, Portland cement, Silica fume**

I. INTRODUCTION

Infrastructure when referring to the Indonesian Language Dictionary (KBBI), it means infrastructure. Understanding infrastructure is a physical system that provides transportation, drainage, irrigation, buildings, and other public facilities, where these facilities are needed to meet various basic human needs, both economic needs and social needs. Infrastructure development aims to facilitate all human activities in all fields. Currently, there are many technologies used in infrastructure development efforts to facilitate and accelerate development so that time is used more efficiently and minimizes failures.

The technology that is emerging rapidly in the infrastructure sector today is 3D printing. 3D printing is an emerging manufacturing technology for producing three-dimensional objects with the help of digital models. Recently, development in the world of infrastructure has been carried out for concrete extracted using 3D printing technology which can also be called 3D printing concrete (3DPC). Usually, concrete is placed into the formwork to make building components, but sometimes it still takes a long time and a lot of energy to install. With this method, there is no need for formwork anymore, so it saves more on production costs.

Many studies have been carried out to determine the appropriate concrete for the application of this 3D printing method. In using this method, the concrete must flow without any obstacles and have sufficient early-age strength to support its own load and support the load of the top layer. Fresh concrete must have the right workability and flowability, so as not to cause obstacles when draining the concrete mixture from the 3D machine pipe. 3D printing has generally been successful with polymer materials extracted in a liquid state and then hardened, although there are limitations with increasing scalability.

If you want to use concrete for the construction of a building, then when it hardens, the concrete must meet its compressive strength of at least fc' of 17 MPa for public buildings and fc' of 21 MPa for buildings using the special moment bearing frame system based on Indonesian standard SNI 2847-2019. Binder materials that are often used for the manufacture of 3D-printed concrete are cement, silica fume, and fly ash.

Fly ash can be used as a substitute for Portland cement because it is pozzolanic and can increase the workability of cement with reduced water consumption. The use of silica fume in concrete mixtures aims to produce high compressive strength values in concrete. The high SiO_2 content in silica fume, which reaches 85%-95%, is useful for cement mixtures.

The type of cement that is often used for concrete mixtures is Portland cement. Portland cement is a hydraulic cement produced by grinding Portland cement slag, mainly consisting of hydraulic calcium silicate, and milled together with additional materials in the form of one or more crystalline forms of calcium sulfate compounds and may be added with other additives [1]. The addition of additives must be a concern because errors in the dosage and method of using additives can be detrimental to the quality of the concrete. Therefore, it is necessary to act

[1] Department of Civil Infrastructure Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. E-mail: yuyun_t@ce.its.ac.id
[2] Departmen of Industrial Machine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

with caution in using additional materials by following the instructions for use.

II. METHOD

A. Definition of 3D Printing Technology

3D printing is an additive manufacturing technology that has emerged to produce three-dimensional objects with the help of digital modes. 3D printing has now come to the industrial world. By using this technology, production of infrastructure designs or buildings can be constructed in a layer-by-layer form without the use of formwork. The 3D Printing machine can be seen in Figure 1.

Economically, 3D printing is faster and more accurate for the construction of complex elements, the cost of the work is low, and it produces no waste at all. In addition, the use of this method also reduces work accidents. However, the use of 3D printing in the infrastructure sector is still lagging in other fields.

Figure 1. 3D printing machine

B. 3D Printing Machine

The printing process for 3DPC mixtures basically consists of three different stages. G Code generation, preparation for transfer of materials to the printer, and printing stage. First, the 3D model is prepared using a CAD program or other application. The prepared model is exported to a file in STL (Stereolithography) format, which is a popular format for the 3D printing industry. Then, the 3D model is processed with the help of the slicing program and a G Code is generated. Model building is accomplished by transferring the generated G code to memory. The next step involves mixing the cement material for the molding process. While the material is being prepared, the molding process is carried out using a hopper-pump-nozzle system. The printing process is completed by printing the structure drawn in the CAD program.

C. Material Preparation

Portland cement is a fine material consisting of the main mixed ingredients such as lime, silica, alumina, iron, and gypsum. Cement is also called a hydraulic binder because when cement is in contact with water, it becomes a chemically active mixture. In a concrete mixture, the paste formed from a mixture of cement and water will then harden, and in a state of binding the aggregates it will produce hard and strong concrete.

Fly ash is a fine residue that results from burning coal in the form of a powder that is carried by gases from the combustion zone to the particle filtration system according to ACI 232 2004. Fly ash is a coal combustion waste which is fly ash which is very fine round and has a pozzolanic nature. Type C fly ash is fly ash containing CaO above 10% which is produced from burning lignite or sub-bituminous coal (light coal). For type C fly ash, the total content of SiO_2, Al_2O_3, Fe_2O_3 is greater than 50%. CaO levels reached 10% [1]. In the concrete mixture, the amount of fly ash used is 15% -35% of the cylinder weight.

Silica fume is a fine pozzolanic material with a higher silica composition produced from blast furnaces or silicon residues. The use of silica fume in ordinary concrete mixtures is intended to produce concrete with high compressive strength (fc' = 50 – 70 MPa at 28 days). The use of silica fume can be up to 30% with a water-cement factor of 0.34 – 0.28 with or without a superplasticizer.

Sand is a fine aggregate resulting from natural disintegration of rock or sand and has a grain size where the grains can penetrate a 4.75 mm sieve according to ASTM C33-03. Sand is made of silicon dioxide and comes from limestone

Superplasticizer is an additional material that is inserted into fresh concrete which functions to increase the slump value to facilitate workability. Superplasticizers can also improve the quality of concrete due to reduced water usage so that the water-cement factor becomes lower with a binding slump. From research [2] was found that the optimal levels of superplasticizer and retarder for workability were 1% and 0.5% of the weight of the binder.

D. Mix Design Mortar

This mix design refers to former experiments which showed bonding in the fresh state of this molding process are extrusion and buildability [2]. The following are the results of the mix design calculation with the addition of 0.8% superplasticizer, with a ratio of 65% filler and 35% binder:

TABLE 1.
MIX DESIGN

Material	Volume	Unit
Sand	1353,56	kg/m^3
PCC	366,251	kg/m^3
Fly Ash	128,188	kg/m^3
Silica Fume	51,2752	kg/m^3
Water	183,126	kg/m^3
SP	5,831	kg/m^3
W/C ratio	0,5	Unitless

E. Reserch Testing Parameter

After planning the mix design, it is necessary to determine the standard of mortar testing. This test is carried out to meet the needs of the material for 3D Printing. the material to be included in 3D printing is in the form of material that has a setting time that is not too fast, has high flowability to pump-pipe-nozzle system from the 3D printing machine and the compressive strength of mortar which must reach the planned target. The research testing parameters and standards and code can be seen in Table 2.

TABLE 2.
RESEARCH TESTING PARAMETER

Tests carried out	Test standard	Test tool	Standard value
Flowability	(ASTM C230/C230, 2014)	Flow table	Experiencing a minimum expansion of 18 cm and a maximum of 24 cm
Setting Time Test	(ASTM C 1117 – 89)	Vicat Tools	The needle has decreased at the point of 10 mm.
Compressive Strength	(ASTM C109/C109M-16a, 2016)	Analog/digital compression engine	17 Mpa (3 days), 24 Mpa (7 days), 34 Mpa (28 days)

III. RESULTS AND DISCUSSION

A. Setting Time Mortar 3D Printing

In this section, we will explain the setting time testing on mortar using the vicat tool. Testing is done by making three mix designs. Each mix design has several different characteristics of the variables with the names M1, M2 and M3. The first mix design, added a superplasticizer with a concentration of 0.8%. then the second mix design, adding superplasticizer with a concentration of 0.7%. and the third or final design mix, adding 0.8% to the ratio of 70% fine aggregates and 30% cementitious.

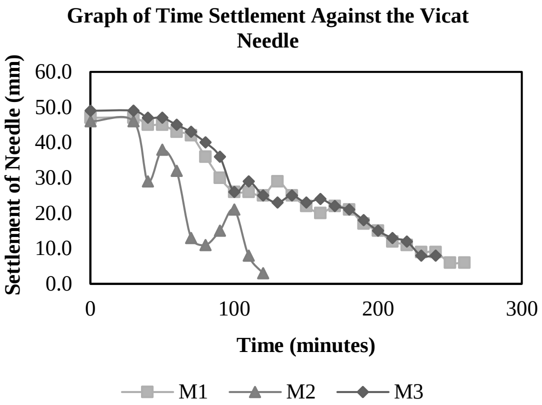

Figure 2. Results settlement against needle vikat

Based on Figure 3, it shows that there are similarities in the test results on the specimen code M1 and M3. Where the mix design of specimen M1 produces a longer setting time of 260 minutes than the mix design of specimen M3 results. While in mix design of the specimen M2, the setting time value is 120 minutes faster than the other mix designs. This indicates that the addition of 0.8% superplasticizer will produce an optimal setting time.

B. Flowability Test

Flowability testing on specimens made using a test tool called a flow table. Flowability testing using a flow table shows the flowable results from M1 which is 144.5%, M2 96.75%, M3 83.75%, fly ash material has round grains so as to increase the flowability [2], ACI 116R-90 determine the flowable material has a flow value of 125% so that the flowable mortar is M1. Figure 3 show the result of flowability test.

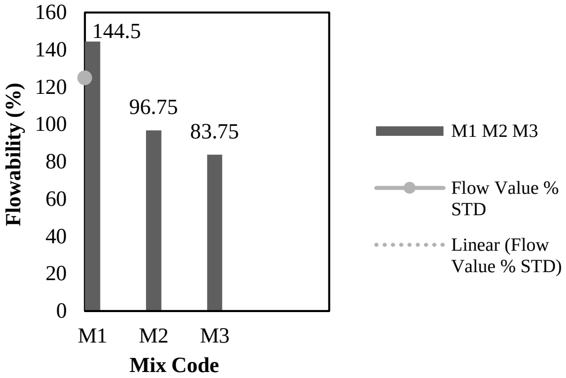

Figure 3. Result of flowability test

C. Compressive Strength

The compressive strength test was based on ASTM C270 - 14a Table 1 and ASTM C1329-16a Table 1, which stated that the compressive strength of mortar material was measured at 1 day, 3 days, 7 days, and 28 days. The mortar is soaked in Calcium Hydroxide solution ($Ca(HO)_2$) before the compression test is carried out. The compressive strength test was carried out at the LMSG (Building Structural Materials Laboratory) ITS civil diploma campus. The compressive strength can be shown in Figure 4.

Figure 4. Compressive strength test on mortar

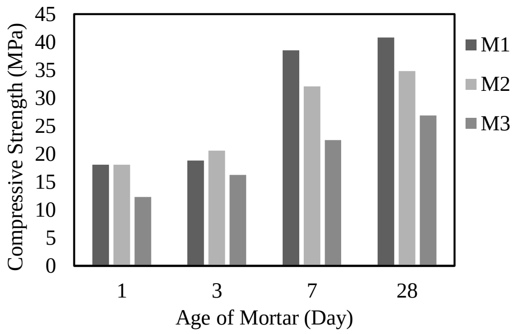

Figure 5. Compressive strength result

Based on Figure . shown that specimen M1, M2, and M3 proficient an increase in compressive strength from 1 day, 3 days, 7 days to 28 days. The specimen M1 has a compressive strength value of 28 days 40.80 MPa, M2 34.80 MPa, specimen M3 has a 7-day compressive strength value of 22.47 MPa. Of all the mix designs tested, all of them met the 28-day compressive strength of 17.2 MPa, so that the compressive strength in this test met all of them.

The addition of fly ash and superplasticizer to the mortar mix can increase the durability of the concrete, besides the addition of the superplasticizer to the mortar mix can improve the concrete compressive strength as a result of the reduction in water usage, so that the w/c becomes decrease with increased slump.

IV. CONCLUSION

Based on the testing and analyzing method and composition of 3D Printing mortar with the addition of a superplasticizer, it can be determined the addition of superplasticizer greatly affects the workability of concrete. The mortar specimens are strongly influenced by the superplasticizer content, because if there is too much addition of superplasticizer there will be abrasion of the mortar mix. The composition of the mortar that has the highest compressive strength value is in the M1 composition, namely sand 1353.56 kg/m^3, PCC 366.251 kg/m^3, fly ash 128.188 kg/m^3, water 183.126 kg/m^3, SP 5.831 kg/m^3, by obtaining compressive strength of 40.8 MPa at the age of 28 days. Testing flowability using a flow table test tool. The test results using a flow table show that the M1 value meets the requirements as a flowable material and can be used as a 3D printing material, where the flow value of M1 is 144.5%, exceeding the requirements in ACI 116R-90 which is 125%. M2 is 96.75%, and M3 is 83.75%, so it is not recommended as a 3D printing material

REFERENCES

[1] *Semen Portland,* SNI 2049-2015, 2015.

[2] Trimurtiningrum and J. J. Eakput, “Geopolymer Grout Material,” *Materials Science Forum,* vol. 841, pp. 40-47, 2016.

[3] I. Rochmanhadi, *Alat-Alat Berat dan Penggunannya.* Jakarta:YBPPU, 1992.

[4] K. P. Umum, *Katalog Alat Berat.* Jakarta Selatan: Kementrian Pekerjaan Umum, 2013.

[5] A. Husen, *Manajemen Proyek.* Serpong: Andi Offset, 2010.

[6] I. W. D. Lenggogeni, *Manajemen Kontruksi.* Bandung: PT Remaja Rosdakarya Offset, 2013.

[7] A. S. Sastraatmadja, *Analisa (Cara Modern) Anggaran Biaya Pelaksanaan.* Bandung: Nova, 1984.

[8] R. Widianto and Sumarman, "Analisi Manajemen Konruksi pada Proyek Pembangunan Jembatan Siliwangi di Sungai Cisanggarung Kabupaten Kuningan," *Jurnal Kontruksi,* vol 7, no. 3, 2018.

[9] I. Ridkiani, "Metode Konstruksi Jembatan Prestressed Ditinjau dari Segi Rencana Anggaran Biaya dan Rencana Waktu Pelaksanaan," *Jurnal Online Mahasiswa (JOM) Bidang Teknik Sipil,* vol. 1, no.1, 2016.

[10] M. Gunawan, R. R. Lorens, G. B. Wijaya, and H. Sugiharto, "Metode Kantilever Pelaksanaan Jembatan Rangka Baja SEI Putting Bentang 60 M," *Jurnal Dimensi Pratama Teknik Sipil,* vol. 8, no.1, 2019.

[11] Ismerianto, S. M. Nuh, and Syahrudin, "Metode Pelaksanaan Struktur Atas Jembatan Tayan," *JeLAST : Jurnal PWK, Laut Sipil, Tambang,* vol. 6, 2019.

[12] P. P. Persero, “Work Method Statement”, 2020.

[13] S. F. Rostiyanti, *Alat Berat untuk Proyek Kontruksi.* Jakarta: Rineka Cipta, 2008.

[14] P. M. P. U. D. P. Rakyat, “Pedoman Analisis Harga Satuan Pekerjaan”, 2022.

[15] M. P. U. D. P. Rakyat, “Pedoman Sistem Manajemen Keselamatan Kontruksi”, 2021.

[16] H. G. Sahin and A. M. Aghabaglou, "Assessment of materials, design parameters and some properties of 3D printing concrete mixtures a state of the art review," *Construction Building and materials,* vol 316, 2021.

[17] T. T. Le, S. A. Austin, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, "Mix design and fresh properties for high performance printing concrete," *Materials and Structures,* pp 1221-1232, 2012.

[18] *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement,* ASTM C230/C230M, 2014.

[19] *Standard Guide for Measurment of the Rheological Proporties of Hydraulic Cementous Paste Using Rotational Rheometer,* ASTM C1749-17a, 2017.

[20] *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement,* ASTM C596-09, 2017.

[21] *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2- in. or [50-mm] Cube Specimens),* ASTM C109/C109M-16a, 2016.

[22] C. Gosselin, R. Duballet, Ph. Roux, N. Gaudilliere, J. Dirrenverger, Ph. Morel,"Large-scale 3D printing of ultra-high performance concrete a new processing route for architects and builders," *Material and Design,* vol. 100, pp. 102-109, 2016.

[23] G. Ma and L. Wang,"A critical review of preparation design and workability measurement of concrete material for largescale 3D printing," *Frontiers of Structural and Civil Engineering,* vol. 12, pp. 382-400, 2017.

[24] R. Lediga and D. Kruger, "Optimizing Concrete Mix Design for Application in 3D Printing Technology for the Construction Industry," *Solid State Phenomena,* vol. 263, pp. 24-29, 2017.

[25] M. Papachristoforou, V. Mitsopoulos and M. Stefanidou, "Evaluation of workability parameters in 3D printing concrete," *Procedia Structural Integrity,* vol. 10, pp. 155-162, 2018.

[26] *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,* ASTM C618-22, 2014.

[27] P. Suraneni, L. Burris, C. R. Shearer, and R. D. Hooton, "ASTM C618 Fly Ash Specification: Comparison with Other Specifications, Shortcomings, and Solutions," *Aci Materials Journal,* pp. 157-167, 2021.

[28] A. Agusti and R. S. Riwayati, "Pengaruh Penambahan Superplasticizer Terhadap Kuat Tekan Beton K-400 Pada Umur 28 Hari," *TEKNIKA: Jurnal Teknik,* vol. 8, pp. 77-84, 2019.

[29] R. Hugo, "Pengaruh Penambahan Silica Fume Dan Superplasticizer Pada Self Compacting Concrete (SCC)," *Prosiding Kolokium Program Studi Teknik Sipil (KPSTS) FTSP 2017,* 2017.

[30] R. Duballet, O. Baverel, and J. Dirrenberger, "Classification Of Building Systems For Concrete 3D Printing," *Automation in Construction,* vol. 83, pp. 248-258, 2017.

[31] Q. Munir, R. Peltonen, and T. Karki, "Printing Parameter Requirements for 3D Printable Geopolymer Materials Prepared from Industrial Side Streams," *Materials,* vol. 14, pp. 1-19, 2021.

[32] T. Wangler, "Digital Concrete: Opportunities and Challenges," *RILEM Technical Letters,* pp. 68-75, 2021.

[33] S. C. Ligon, R. Liska, J. Stampfl, M. Gurr, and R. Mulhaupt, "Polymers for 3D Printing and Customized Additive Manufacturing," *Creative Commons Attribution,* pp. 10212-10290, 2019.

[34] F. Bos, R. Wolfs, Z. Ahmed, and T. Salet"Additive Manufacturing Of Concrete In Construction: Potentials And Challenges Of 3D" *Virtual and Physical Prototyping,* vol. 11, pp. 209-225, 2016.

[35] S. Lim, R. Buswell, T. Le, R. Wackrow, S. Austin, A. Gibb, T. Thorpe, "Development Of A Viable Concrete Printing Process," *Proceedings of the 28th ISARC, Seoul, Korea,* pp. 665-670, 2011.

[36] Wilwin and A. Sutandi, "Studi Identifikasi Risiko Pada Proyek Infrastruktur Di Indonesia," *Jurnal Mitra Teknik Sipil,* vol. 4, pp. 295- 302, 2021.

[37] *Persyaratan Beton Strukturan Untuk Bangunan Gedung Dan Penjelasan,* SNI 2847:2019, 2019.

[38] M. Setiawati, "Fly Ash Sebagai Bahan Pengganti Semen Pada Beton," *Prosiding Seminar Nasional Sains dan Teknologi,* pp. 295-302, 2018.

[39] W. S. Wicaksono, W. Wibowo, and E. Safitri, "Pengaruh Kadar Silica Fume Terhadap Kuat Tekan Pada High Strength Self Compacting Concrete (HSSCC) Benda Uji Silinder D 7,5 Cm X 15 Cm Usia 14 Dan 28 Hari," *Matriks Teknik Sipil,* vol. 6, pp. 638-644, 2018.

[40] N. Nadia and A. Fauzi, "Pengaruh Kadar Silika Pada Agregat Halus Campuran Beton Terhadap Peningkatan Kuat Tekan," *Jurnal Konstruksia,* vol. 3, pp. 35-43, 2011.

[41] S. P. Hapsari, W. Wibowo, and E. Safitri, "Kajian Pengaruh Variasi Komposisi Silica Fume Terhadap Parameter Beton Memadat Mandiri Dengan Kuat Tekan Beton Mutu Tinggi," *Matriks Teknik Sipil,* vol. 5, pp. 1449-1456, 2017.

[42] A. Basuki, "Pengaruh Penambahan Fly Ash dan Silica Fume terhadap Daya Tahan Penetrasi Air Beton Normal," *Jurnal Teknologi Bahan dan Barang Teknik,* vol. 5, pp. 21-28, 2015.