

# Mix Design and Printability of Concrete for 3-D Printing

*A Thesis submitted in partial fulfillment of the requirement for the award of degree of*

MASTER OF ENGINEERING  
IN  
STRUCTURES

Submitted By

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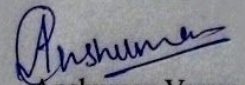
DEPARTMENT OF CIVIL ENGINEERING  
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## DECLARATION

I, ANSHUMAN VERMA hereby declare that the work presented in this thesis entitled “**Mix Design and Printability of Concrete for 3-D Printing**” in partial fulfillment of the requirement for the award of degree of **Master of Engineering in Structural Engineering** and submitted in **Civil Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala** is an authentic record of work carried out under supervision of **Dr. Shweta Goyal, Associate Professor, Dr Naveen Kwatra, Professor, Department of Civil Engineering** and **Dr. Tarun Kumar Bera, Associate Professor, Department of Mechanical Engineering, TIET, Patiala** from July 2018 to August 2019.

The matter presented in this thesis has not been submitted either in part or in full to any other university or institute for the award of any other degree.

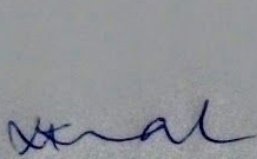
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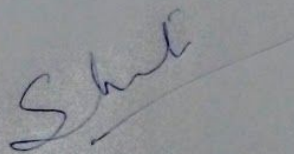
## CERTIFICATE

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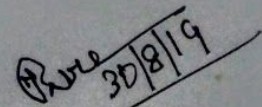
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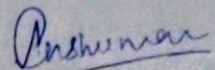
I would like to express my profound gratitude to **Dr. Shweta Goyal, Associate Professor and Dr. Naveen Kwatra, Professor, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala**, for their unwavering support and motivation throughout this project.

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## **ABSTRACT**

Every industry in the world is moving towards automation, making things more mechanized and self-driven. Automation has been accepted successfully across every sector due to high accuracy, precision and cost and time efficiency. Concrete industry despite being one of the major industries in the world is still striving in the field of automation, as this term is relatively new in concrete technology. 3-D concrete printing is full automation of the construction practice and has the ability to transform the process completely and making it error free.

A lot of researchers and companies are working on this topic extensively for a broader parametric study of the process and to achieve better precision that this process is capable of providing. In this study, various parameters related to the 3-D printed concrete were discussed which indicates the printability of concrete. For this purpose, a setup was developed similar to a printer, which extruded concrete to a printing bed. A mix design was designed to be tested on this setup with varying w/c ratio and SP dosage and samples were printed. Then different parameters were analyzed and compared by changing the mix design composition to improve the printability of the concrete.

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# CHAPTER 1

## INTRODUCTION

### 1.1 GENERAL

Various drivers are pushing development towards automation, reducing costs and/or on the other hand to increment building opportunity. There are various instards mechanization: reducing the workforce for safety and efficiency issues, optimization of construction time, removing errors; prices of automation such as automatic brick laying [1], sprayable concrete [2], precasting technology [3] robotic/ computerized milling by the help of which construction panels are created and shaped for complex structures [4]. The improvement in BIM will without a doubt rise the utilization of computerized data and probably help in automated modelling as well as manufacturing processes by computerized development.

Additive manufacturing (AM) guarantees the completely robotized manufacture of building structures when complex structures and multifaceted nature comes without any additional expense. Contrasted with ordinary construction, AM techniques are comes with benefits like development of components with great geometric complexity even if the quantity of components is very few. In this manner, AM is foreordained for production process where component development and complexity of structure is demanded. Concrete is known for its ability to be molded in any required form or shape. Inspiration is that the concrete construction is limited to the ordinary shapes and most importantly with a uniform cross-section has proved to be staggering expense of free-form formwork.

The level of automated construction process, despite concrete is known to be a typical material in the construction industry, is not adequate. AM has ability to revolutionize this industry. Different additive fabrication strategies, particle bed 3-D printing empowers creation of form free concrete parts without the necessity of complex and costly formwork and Machinery. Hence, this method is capable of creating the balance in geometric optimization and high construction cost and making complex design solutions reasonable. It can extend the feasibility of financially viable shapes and increase the use of design solutions.



**Fig 1.1: 3D printed concrete structure without formwork**

Environmental hazards that construction industry poses to world increasing the carbon content could be controlled by integrating 3-D printing with different techniques. Concrete members with streamline shapes can reduce the consumption of materials, decreasing the size of the members hence decreasing the energy consumption too. The optimization of the shapes of the members can decrease the consumption of concrete and reinforcement by up to 70 percent. The damage caused by this industry on the environment is heavy, responsible for 40% of energy consumed, 38% of substance release, which causes ozone hole, 12% of drinkable water, and most importantly the total solid dump that is generated is almost 40% of total and carbon dioxide release due to manufacturing of cement is 5–7% [5–9]. So saving materials in construction can impart high effect on environment as well as the cost of a project.

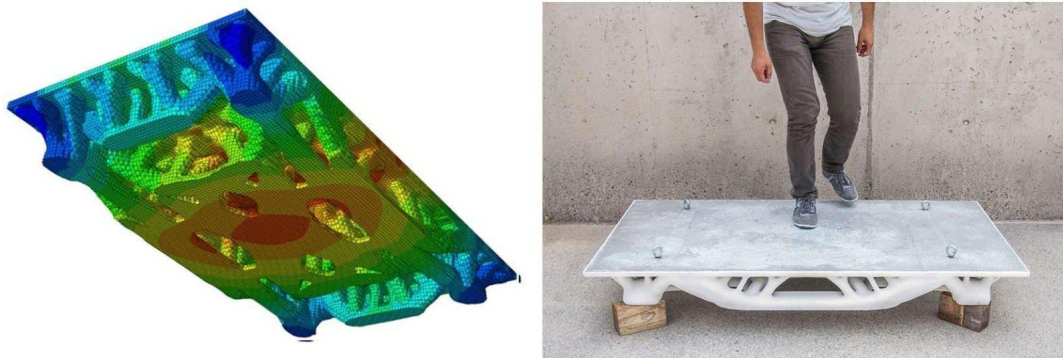
## **1.2 3D PRINTING**

There are different procedures where substances are solidified and joined with the help of computerization making a 3-D structure, with substances included together, one of such procedures is called 3D printing. The term 3D printing originally referred to a procedure that stores a binder material onto a powder bed with inkjet printer heads layer by layer. Even more as of late, the term is being utilized in popular vernacular to encompass a more extensive assortment of additive manufacturing techniques. It is commonly referred to as Additive Manufacturing.

### 1.3 ADDITIVE MANUFACTURING AND 3D PRINTING

The term AM have increased wide prevalence Motivation was subject of different materials are being added together. Still 3D printing is alluded distinctly with the use of polymers for the manufacturing and having a wide application in metal forming.

3-D printing is being utilized in popularly by purchaser creator networks and the media, and additive manufacturing was utilized all the more officially by machine manufacturers, worldwide technical standards organizations, and industrial end-user part makers, . Until recently, 3-D printing was related to machinery which was of low price or have smaller capability. The terms terms 3-D printing and AM mirror that the technologies share the subject of material addition or joining all through a 3D work envelope under mechanized control. Terms are still often synonymous in easy-going use however few specialists explains the 3-D printing is a type of AM.



**Fig 1.2: a slab prototype, material efficient**

### 1.4 ADDITIVE MANUFACTURING IN CONSTRUCTION INDUSTRY

Printing process is in three phases: preparing the model, mixing concrete and printing of the structure. The first phase is to design a three dimensional model in CAD. A detailed model and parameters on the structure has to be defined in the model. Also the model should be calibrated with the capabilities of the machinery. Mixing of concrete is the next step in the process. A careful mix has to be designed so as to be printable and to be used in an automated machinery. A lot of research has to be done before introducing the concrete into machinery because a lot of issues can be faced or generated in this process as concrete changes its form

with time. After concrete is mixed and ready in a container it has to be supplied to a printing head or a nozzle for printing in a 3-D frame where it is printed.

#### 1.4.1 Modeling

3D printable models can be created with a computer-aided design (CAD) bundle. CAD created 3-D models are progressively exact and can be amended before printing. The manual demonstrating the process of preparation of geometric information for 3D computer graphics is similar to plastic arts, for example, sculpting. The process of gathering digital data on the shape and presence of a real object, making a digital model based on it is called 3D scanning. Computer aided design models are saved in the file format (STL). STL stores information based on calculations of CAD models. It's not intended for using in AM because generated document sizes of topology optimized segments and lattice structures is enormous, because of the huge number of surfaces included. A more current format, the AM File format (AMF) has been used to take care of this issue. This software stores data utilizing technique called curved triangulations.

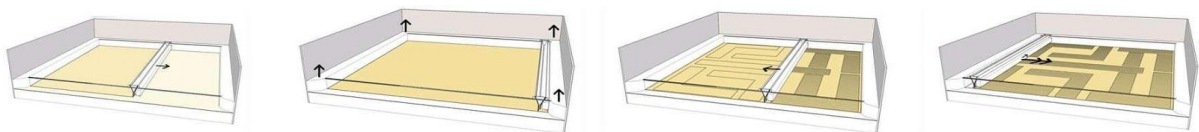
#### 1.4.2 Printing

Pegna[10] made the first ever attempt to use cement in a AM technique using a mortar and laying of bricks. But today a lot of new processes has been developed using concrete in various form to print 3-D elements. Few of them are Contour Crafting [11], D-Shape printer [12] and 3-D Concrete-Printing [13]. Successful manufacturing of various kinds of shapes and forms has been achieved with these technologies.



**Fig:1.3 D Shape 3-D printer (left) printing head (right).**

These processes have been used for pre manufacturing of components and placing those components on the site at a later stage. But some of them are being used on the site and the capabilities are continuously expanding. D-Shape is a printer with in which a gantry frame is set up making the movement of the frame in all three dimensions. A print head to this frame. D-shape is based on the principle of deposition of materials in powdered form which is activated by the binder jetting and making the material stiff to stay in place. Another technique called Z-Corp printer is also used in plant manufacturing of elements. Layers of desired length are laid on the printing bed in the form of dry material and the binder is ejected in the desired shape to harden the material layer and the process is repeated to get the structure of desired height.



**Fig:1.4 Printing of layers with AM process.**

Contour Crafting depends on extruded concrete retained by the nozzle itself providing a smooth finishing to the layer extruded. The object is created by extruding multiple layers as the concrete is laid on the surface. The goal of the process to achieve the Rapid construction of structures. This process has a print head mounted on a crane to provide ease of mobility in 3 D space. This process is quite efficient in printing on site.

### **1.4.3 Finishing**

Printing marginally larger objects in large resolution, then the removal of excessive material by higher resolution subtractive manufacturing techniques give high precision, but this is a very time consuming process and the cost of construction increases due to an additional process.

Improved smooth surface completion can be acquired by using chemical vapor procedures dependent on acetone or comparative solvents, in the event of printable polymers like ABS. They are additionally equipped for utilizing different materials over the span of developing parts. A few strategies needs interior backings for cantilever components of structure while manufacturing. The backings has to be removed or disintegrated after completing printing procedure.

## **1.5 CONCRETE USED IN 3D PRINTING**

Concrete is typically put in formwork and vibrations are given to manufacture members. Two other technologies have been development, self-compacting concrete and sprable concretes. Essential guideline for SCC is that aggregates structure is left with minimum void content. a high superplasticizer dosage is given, and the gaps in the particles are filled making the concrete highly flowability. But the major drawback is that SCC still requires a formwork A lot of time is consumed in the placing the formwork moreover the geometrical restrictions are again there making is difficult to construct complex structures. Sprayed concrete is the technique in which components are formed by spraying concrete against temporary formwork and when the component is casted, the formwork has to be disposed. to facilitate this process high binder content should be there in the concrete which improves the adhesion a strong structure can be developed. The spray pipes has to be lubricated from inside so there are no blockages. There is considerable reduction in the form work in this method but issue is with imprecise shape of the component. 3D printing is a new method of building objects without any form of formwork. This method is utilised to form complex members without any sort of formwork. Printing concrete is a technique in with features of both SCC and sprayable concrete are present. But there are issues associated with this method like there can be a blockage in the printing system so there is uncertainty weather material inside would be extruded or not. Also there can be settlement or flow of any layer that has been extruded from the printer. So the concrete must have enough flowability so as to pass through the machine and should have enough strength to bear the weight of the layers above it. If it doesn't have enough strength it would crumble with the load but the setting shouldnt be so high that there is no bonding strength between the layers.

## **1.6 DESIGN MIX OPTIMIZATION CHALLENGES**

For optimizing the procedure, two noteworthy issues has to be resolved: holding in different layers which is a significant issue in the printing. The quality of the structure printed differs with the interval provided in the layers. Another issue in the printed concrete is with the solidification the concrete. It must becomes solid enough so as to retain upper layers but at the same time it should not get hard to the extent at which there is no adequate bonding between the layers.

The interval between two extruded filaments should be sufficiently high so that the strength of concrete is attained to bear the deposited layers and it should be low adequately so that there is strong bonding between layers. Ability of printed concrete to bear the load of the deposited layer to retain its own shape is linked to the rheological aspects and the shear stress. Shear stress should be high to provide stability to the layers and to the structure. But another issue is that the concrete must be fluid enough to serve the requirement of extrudability.

### **1.6.1 GOALS TO BE ACHIEVED FOR OPTIMAL MIX**

Augmenting the compressive strength, however to maximize compressive strength, water cement ratio has to be minimum. Be that as it may, a specific water-cement ratio should be maintained so that the concrete is workable enough. Workability and flowability should be high in printable concrete to make it extrudable but at the same time, concrete has to be buildable once it is poured, holding its own weight and the upper layers that has to be laid over it.

Amplify speed of concrete setting while keeping up proper setting rate in order to guarantee bonding with the consequent layer. However a monolithic structure has to be built despite the layered fabrication. Buildability is dependant on the workability of the concrete and its change with time. The open time must be high to facilitate the flow of concrete else the material will gain some hardness and would block inside the pump also imparts high extrudability and improved inter layer bonds are formed. But it could cause serious issues as the structure can fall not able to retain its own weight. So these properties are interdependent but contrary. So the ideal conditions has to be created to find a balance between them.

## CHAPTER 2

### LITERATURE SURVEY

**Peled et al. (2000)** studied the rheological effects of flyash on extrudable fibre concrete. Paper plotted ram-pressure vs piston-movement for mixes by changing the amount of fly ash. For polyvinyl alcohol (PVA) as well as acrylic fibres, addition of fly ash decreased the extrusion pressure of the concrete whereas for glass fibres, however there was no change in extrusion pressure by adding fly ash whereas in cellulose fibres, fly ash caused an increment extrusion pressure.

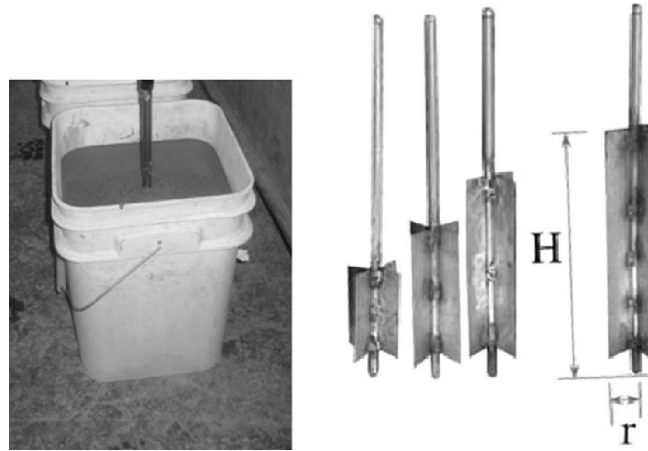
**Voigt et al. (2010)** studied the effect of fly ash, calcined clay were added to concrete, and their effect on flowability of concrete and shape stability of the layers extruded [16]. Flow table test had been used to determine the flowability of concrete and stability of shape was found by green strength determination by load carrying capacity of cylindrical specimens. By adding fly ash flowability was improved but at the same time shape stability of the concrete was reduced. Whereas when the calcined clay was added, shape stability was improved but caused a decrease in the flowability was found. From rheological point of view, combined addition of fly ash and calcined clay was proved to be beneficial. A mixture with good flowability and required shape stability was produced with this combination.

**Tregger et al. (2010)** studied the behavior of concrete with addition of fly ash, calcined clay and high range water-reducing admixture (HRWA) on the green strength of cement paste [17]. Green strength was determined by the load carrying capacity of cylindrical specimens made of green concrete. Green strength of concrete was increased by using calcined clay while there was a reduction in strength of concrete due to the addition of both HRWA and fly ash. Also, compression and shear- yield stresses were examined. The shear yield stress of the green concrete was determined with the help of a strain controlled shear rheometer, having a co-axial geometry. Compression yield stress of green concrete was determined by centrifuge method. Both shear and compression- yield stresses were improved when calcined clay was added while they with addition of fly ash and HRWA, these values decreased.

**T.T Le (2012)** has studied the properties such as extrudability and buildability along with workability and open time of a fine aggregate concrete with fiber reinforced for printing

concrete [18]. While an optimum mix has been identified studying the effect of superplasticizer, accelerator, retarder and fibers. Two older approaches called self-compacting and sprayed concretes have been discussed which were cost inefficient and consumed huge amount of time as compared to concrete printing. The construction or setup of concrete printing machine has been discussed. The three-stage process required for 3D printing i.e. data preparation as 3D CAD model, concrete preparation i.e. creating the mix and transferring it to machine and component printing are discussed. For the mix design, 9 mm diameter was chosen with maximum 2mm size sand. The binder was cement CEM type I. The superplasticizer used was polycarboxylate based. Amino-Tris, formaldehyde and citric acid were combined to form a retarder. To study extrudability fresh property, it was tested for filaments which were 9mm wide. The workability was measured every 15 minutes using the shear vane. In his results and discussion section, he has given that 5 mixes were created in which the sand content was reduced in 5% decrements and binder content was increased from 25 to 45% respectively from Mix 1 to Mix 5. By adding more superplasticizer to Mix 3 and 4, the mix was extruded from nozzle whereas this was not the case for Mixes 1 & 2 and the Mix 4 was found to be optimum but was later investigated for buildability, workability, open time etc. After investigating workability for all the mixes, he found that superplasticizer was required to get workability. After similar observations for open time and buildability, the printing was started. The print design had a length of 2m, width of .9 m, was 0.8 m high and consisted of 128 layers. Finally he concluded that optimal mix should have 3:2 sand binder ratio, 70% cement, 20% fly ash, 10% silica fume, 1.2Kg/m<sup>3</sup> of 12/18 mm length fibers to be printed by a 9 mm nozzle to build 61 layers maximum in one session.

**Khayat et.al. (2012)** discussed one of the major issues concerning the printability of motor [19]. It discusses the dilemma between flow ability and thixotropy of concrete. At one side, the concrete must be flow able enough to be pumped through the system and at the same time concrete should have high thixotropy to retain its shape once it is pumped out of the nozzle so there are no vertical or horizontal deformations in it. The paper suggests some field-oriented tests to evaluate this structural build-up of concrete with time portable vane test, which is normally used for evaluating shear stress in soils was used. Reading of dial gauge indicating torque were taken after four rest times. Different vane sizes were used. Largest size was used for weakest structure and vice versa. This method gives shear stresses variation in concrete with time. This paper also suggests another method for evaluating structural build i.e. undisturbed slump spread.



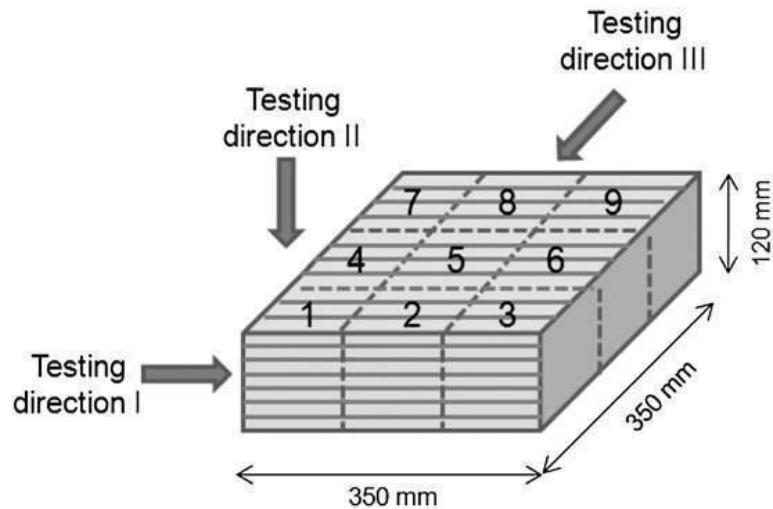
**Fig 2.1: Portable Vane test**

This particular method was more basic and is similar to the slump flow test. In this test, mould with filled concrete sample is lifted up slowly and material is allowed to flow freely without any vibrations on an impervious base. Two mutually perpendicular readings of diameter are taken and were averaged to get diameter of flow. As there are no standardized tests available to measure structural buildup of concrete, this paper suggests some tests that could be performed to evaluate this property.



**Fig 2.2: Spread of mortar at four spread of USS test**

**T.T. Le et.al. (2012)** stated that a “high performance printing” concrete was developed at Lough borough university [20]. A 200mm Lang bench was printed by the 3-D printed. 100mm cube specimens were more casted, some extracted from 350×350×120 mm, and 500×350×120 mm slabs were tested for compressive strength for different directions.



**Fig 2.3: Loading directions for compressive strength test**

This experiment showed a 15% reduction in the sample extracted from a printed slab as compared to mould casted specimens whereas the reduction was as high as 30% in curved printed specimens. The compressive strength was further lower when testing plane is parallel to the loading applicator to it than the compressive strength results of other two loading directions.

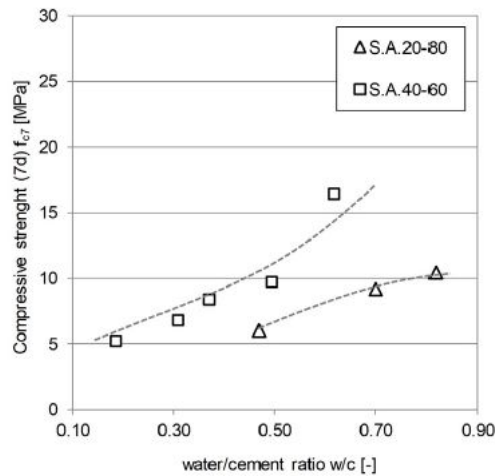
**Zeina Malaev (2015)** in his paper the author has used 3D concrete printing and tested his experiments for fresh and hardened concrete properties [21]. The mix design that he created was based on to achieve goals such as maximizing compressive strength, maximizing workability, maximizing flow ability etc. In addition, it discusses the machine design, nozzle design, tank and pump design along with mix design. The test performed by him ensured extrudability, compressive strength, flow ability, Buildability and open time. In his work, he tested various mixes for the above mentioned properties which were having various properties of sand, fine aggregate and cement. The extrudability was tested visually and an observation was made that if we decrease the quantity of sand and increase the quantity of cement then better extrudability is observed. In addition, the buildability property was observed, that the layer build decreased as the superplasticizer used to build the layer increases. The flow ability property observed suggested that it should be between 1.0 and 1.2 cm/s in order to have required buildability and workability. The impact of adding accelerator is also discussed and how excess of it can affect the extrudability. At last, the author concludes the paper with defining the nozzle diameter as 2cm, which will optimize the extrusion process.

After the experiment, the optimum mix for the above-mentioned properties was found to have Compressive strength of 42 MPa was obtained from this mix.

**Table 2.1: Mix design developed by Zeina Malaev (2015)**

Material	Quantity
Cement	125 gm
Sand	80 gm
Aggregate	160 gm
w/c	0.39
Accelerator	1 ml
Retarder	0.625 ml

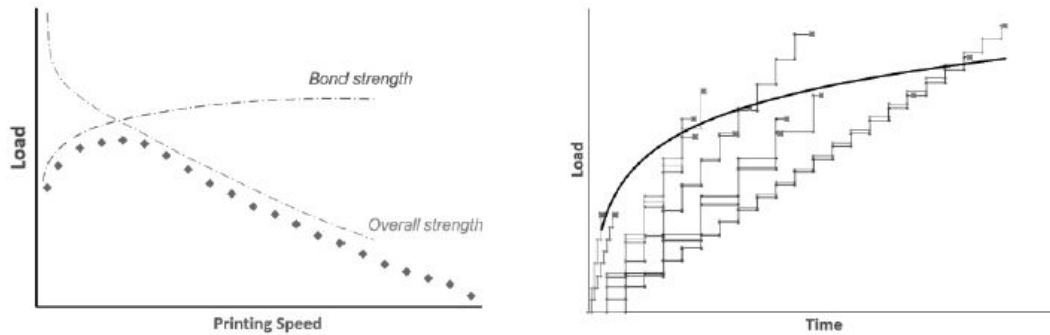
**D. Lowke et.al. (2015)** in this paper, the study of variation of compressive strength with water-cement ratio was analyzed for two different mixtures with two different cement to sand ratios, which are 20/80 and 40/60 [22]. The layer thickness of 1mm was selected for this work. In this work, an unusual trend was observed. Compressive strength of printed samples increases with increases w/c ratio.



**Fig 2.4: Effect of w/c on compressive strength for cement sand ratios 20/80 and 40/60**

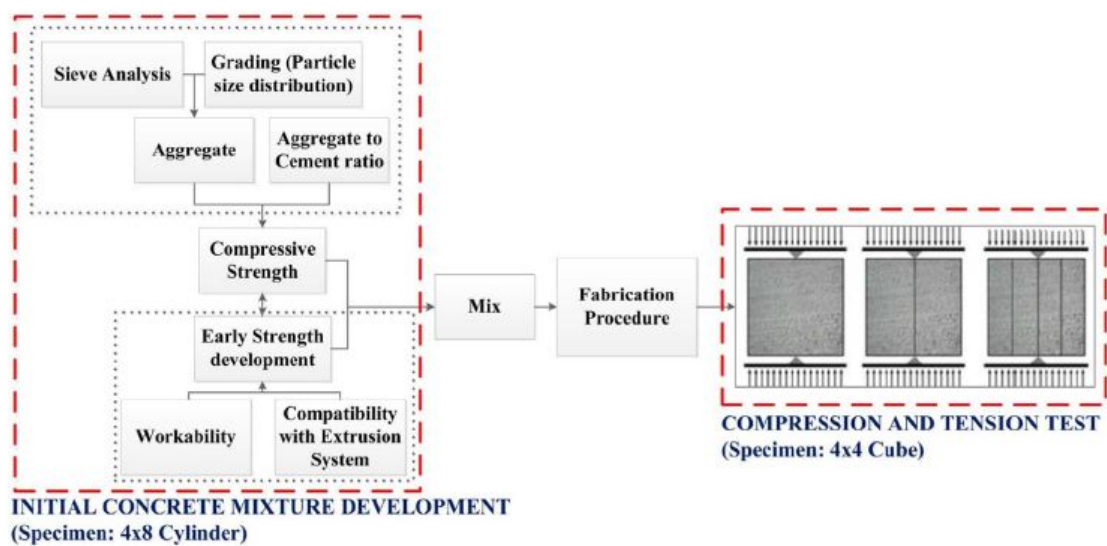
**Salet and Wolfs (2016)** this paper shows comparison between development of strength of green concrete and printed concrete with time [23]. Reduction in compressive strength of concrete was observed with changing printing speed. Therefore, to further investigate the change in compressive strength Bond strength variation of concrete with

printing speed was plotted. Comparison of final compressive strength with varying printing speed was also done with Bond strength. It was observed that bond strength between layers increases at high print speeds but compressive strength decreases. So an optimum print speed was achieved.



**Fig 2.5: Load bearing capacity related to printing speed (left) Development of load bearing capacity of green concrete (right)**

**Zareiyan and Khoshnevis (2017)** in this paper, different aspects of interlayer adhesion contour crafting were evaluated with development of an engineered framework [24]. Different parameters of concrete like extrusion rate, layer width, layer thickness were discussed, and their impact on interference boner strength, crack formation and propagation were analyzed.



**Fig 2.6: Research Methodology used by Zareiyan and Khoshnevis**

A definite experimental procedure was defined. Firstly, the effect of aggregate size on compressive strength of concrete was studied. After that, the early strength development of concrete mix was evaluated and a concrete mix which yields optimized early strength with this mix, extrusion rate and layer thickness was fixed and then the bond strength of fabricated layered specimen was analyzed. The researcher observed that the mix with minimum aggregate size yields the maximum compressive strength, split tensile strength. The bond strength of printed specimen is positively influenced by increase in layer height and less open time.

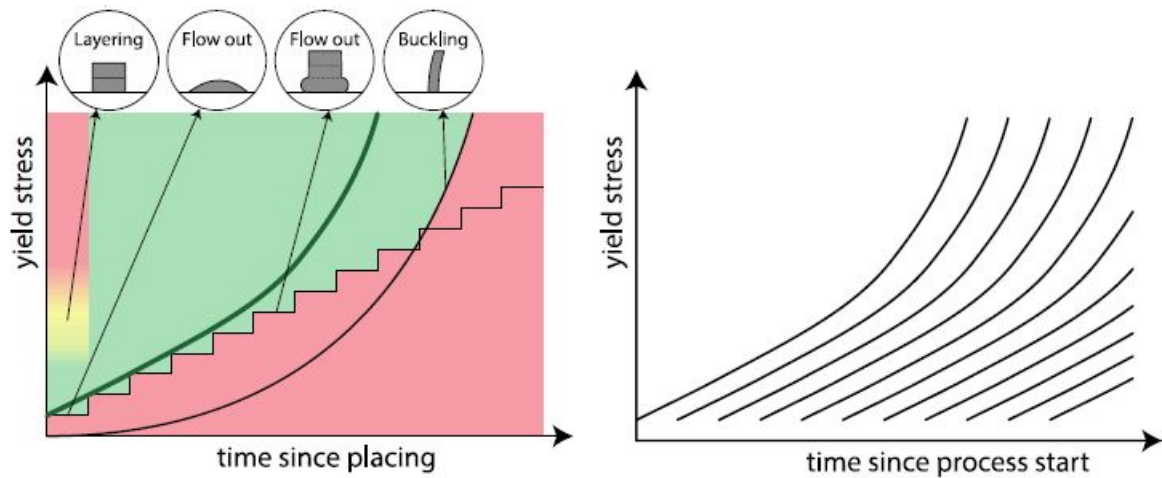
**R.A Buswell et. al. (2018)** studied the relationship between fresh and hard properties of the concrete material and how the geometry of the structure created is affected by these properties [25]. It also suggests the research area to be taken up in future in this engineering field. The paper briefly discusses technical issues in the field of 3DCP (three-dimensional concrete printing) i.e. the fresh properties of materials used and provides some solutions as well. Commenting on the open time pumping and extrusion, he reviewed that the mixtures viscosity and yield stress as described in Table 2.2 were good for extrusion and pumping.

Mix	Yield Stress
CEM and Fly ash	0.5 KPa
CEM and limestone filler	0.27

**Table 2.2: Yield Stress of Mix**

Regarding the extrusion process, it states that until now it is validated by visual inspection only. The paper concludes by the design, finishing, process and materials used in the 3DCP process and how they can be made better in the future.

**Reiter et.al. (2018)** in his paper states that the concrete belongs to the family of yield stress fluids [26]. If applied stress exceeds critical stress, it deforms and behaves as a liquid and below critical stress it acts as a solid. The shear stress of concrete varies with time so this behavior of concrete changes with the time passed after hydration reaction starts.



**Fig 2.7: Yield stress evolution required as a function of age after placing considering layering, flow out and buckling (left) single layer (right) subsequent layers**

At rest or low shear states, shear stress to initiate and maintain flow increases because stress-transferring structure is build and as the flow rate once increases, it breaks down. A yield stress v/s time since placing graph was obtained which states the behavior of concrete at different time zones. An optimal printable region was also derived.

**A.V Rahul (2019)** in his paper, the author has concluded extrudability test, buildability test, Robustness test, flow table test, workability test [27]. Above tests has been done for the prepared mixture namely SF, NC and VM, which has of Portland cement and fly ash. For the reference mix, extrudability test passes when the SP dosage is 0.10. In addition, the buildability test for the reference mix collapsed at 0.11% of SP dosage and was 0.10% of SP dosage. For SF mix, it was shown that for mix SF, extrudability failed when SP dosage was 0/16 and buildability was zero. The yield stress was  $2.6 \pm 0.3$  and flow value was  $55 \pm 5$ . For NC mix, extrudability test failed when SP dosage= 0.11, buildability=0, yield stress=  $2.9 \pm 0.3$  and flow value (%) is  $60 \pm 5$ . For VM mix, extrudability test failed when SP dosage=0.15, buildability=0, yield stress=  $3.0 \pm 0.4$  and flow value (%)=  $40 \pm 5$ . Conclusion of the paper was: Yield stress between 1.5 to 2.5 kPa is good for layer wise buildability. The mix VM was more robust and passes extrudability and buildability tests.

## **CHAPTER 3**

### **EXPERIMENTAL PROGRAM**

#### **3.1 METHODOLOGY**

The test program is designed so as to find properties of materials used for making printable concrete, Designing the 3-D printer, calibration of printer and adjustment of w/c ratio of reference mix, comparing different parameters of fresh concrete with substitution of fly ash with GGBS from 20% to 0% with 5% replacement at each step and then evaluating compressive strength of all the design mixes. This test program was divided into following steps:

1. Firstly the basic properties of all the constituent materials i.e. cement, fine aggregate, silica fume, GGBS and fly ash used as per Indian Standards were determined.
2. A reference mix was selected and designed
3. A basic hand pump (pneumatic type) was used to know the behavior of concrete when applied under pressure by varying water- cement ratio.
4. Modification and fabrication of a scrap air blower to work as a concrete pump.
5. Exploring different options for 3-D moment frames and fabricating a frame for moment of print heads.
6. Evaluating the pumpability of the reference mix and adjusting the Super plasticizer dosage.
7. Evaluating different fresh property parameters of reference mix and with substitution of fly ash by GGBS from 20% to 0% with variation of 5% in each mix.
8. Casting of five different mixes and evaluating the compressive strength.

#### **3.2 DEVELOPMENT OF 3-D PRINTER**

3-D printer is a highly sophisticated machinery, based on a simple concept. A material is pumped to a printing head which is mounted over a movable 3-D frame. The printing head moves in a 3-D space, extruding material in the desired shape. Hence, a required object is printed. To develop a fully working printer there are two different systems that has to be

developed. First is concrete pumping system, through which mixed concrete is pumped from a mixing container to the printing nozzle. The pump has to be so designed so it could pump concrete without causing any blockages, providing a smooth flow of concrete. Second part is a 3-D frame, which allows the free movement of printing head, taking the nozzle to the point where concrete has to be poured.

As 3-D printer is an expensive piece of machinery, which is not commercially available in the market as per now. So, for conducting this research a relatively simple system was developed for the purpose of testing and monitoring the behavior. Basic tests were performed on this developed printer to investigate the behavior of concrete in pumping and printing. This system allowed us to design a printable design mix of concrete. The idea behind this prototype was to make it cost efficient and to study the future scope to develop a full fledged 3-D concrete printer. For achieving this goal different options were investigated to form a low priced basic concrete printer. The following simplified system was finally developed to perform further testing on the material.



**Fig 3.1: Printing assembly while printing**

### **3.2.1 Concrete Pump**

A pump was required to pour concrete on the printing bench to form layered printed concrete. A scrap air blower, used in foundry furnace was taken and modified to make it pump concrete. The air blower was cast iron machinery with a 1 hp motor and Steel blades, worked on a principle of centrifugal pump. There was motor mounted on one side and a hollow disk

with a cylindrical outlet. Blades were inserted inside this hollow disk and were attached to the shaft of the motor, rotating at high r.p.m. The circular plate was fixed in the hollow disk, to cover other end of the blades.

The circular plate was replaced by another assembly. This assembly was fabricated by welding an iron pipe making a bend. One end was attached to plate with a circular opening, replacing the original disk. Other end of the pipe was attached to an inverted pyramid container. Concrete was poured into this container. Concrete was fed to the pump through the bent pipe. A cone was fabricated and screwed to the outlet to reduce the diameter of opening to the diameter of the pipe. A flexible pipe was attached to the cone head and at the other end there was the 2 cm printing nozzle attached.

Specifications of pump:

- a.c. motor
- 1 H.P.
- 1440 R.P.M
- 440 V
- 3 phase power supply



**Fig 3.2: Concrete pump**

### 3.2.2 3-D Frame

The transmission system of the 3-D Printer facilitates the movement of the print head or nozzle that extrudes the concrete, from the pump to the printing bed. A 3-D frame was fabricated having four parts in transmission frame:

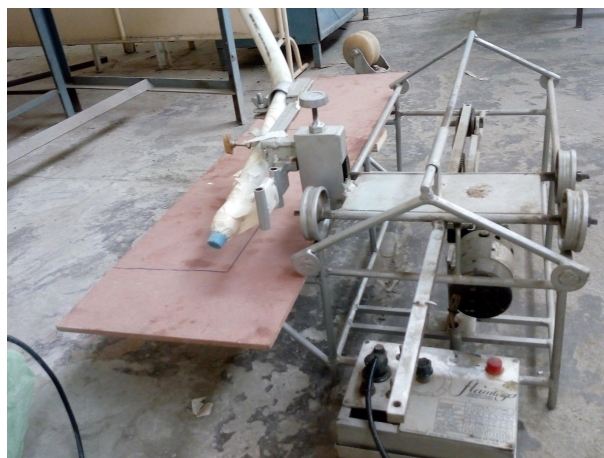
- d.c. motor
- transmission system
- carriage-way
- wheels on which the printing head slides

d.c. motor operates the whole setup. Current input is given to the motor which can rotate at an adjustable rpm to provide a variable speed to the printing head to be adjusted according to the desired output of concrete.

**Table 3.3: Specification of motor in motor in 3D frame**

Revolutions	2 – 22 rpm
voltage	220 – 250V
maximum current	0.35A
torque	0.05663N-m

A regulator was attached with the d.c. motor to vary revolutions of the motor to find the optimum speed of printing of concrete. A forward - reverse button was also added for clockwise and anticlockwise rotation of the motor.



**Fig: 3.3: Printing frame**

A pinion was mounted on the motor shaft which was coupled with a rack through a gear for the reduction of speed. The pinion was having 18 teeth and was attached to the output shaft of motor. The other gear which was attached had 74 teeth.

A rack was attached to carriage way which have a moving plate. The frame was supported by 4 guiding wheels. The guiding wheels had one directional movement, moving over a rail. Movement of print head was facilitated by the rail, to and fro. A sampling frame was fabricated on carriage plate to hold the printing nozzle. A gear was attached in the front to move the carriage clamp in the horizontal direction. This could be used to move from printing in another direction. The whole arrangement could be moved up or down so that the desired height could be achieved and maintained to print the required layer thickness. As a layer was printed the height of the nozzle was raised so as to get the exact space required to lay that concrete layer.

An electric box was attached to this apparatus which was having a 3-way switch that was used to turn the motor forward-off-backwards. The circuit had a rheostat that could control the current supplied to the motor which was used to adjust the r.p.m. of motor that in turn helped to control the printing speed. The maximum speed of 60mm/s could be achieved by the frame.

### **3.3 MATERIALS**

Cement, aggregate, Ground- Granulated Blast furnace Slag, silica fume, fly ash, super plasticizer, fibers and water were used for designing different mix designs for evaluating the performance of concrete with the 3-D printer. Details of the materials used are given below:

#### **CEMENT**

Cement is the most widely spread and most crucial constituent of concrete, which binds, sets and hardens with addition of water. A hydration reaction is triggered and the C-S-H (Calcium Silicate Hydrate) gel is formed around the constituent particles and a cohesive link between them is formed. Although different binding materials having significant binding properties have been developed in the past century, still cement is necessary to initiate hydration. In this particular study, OPC 43 Grade Shree cement, which is available with local

dealers was used to perform all the experimentation. Properties of cement used are given in Table 3.2.



**Fig 3.4: OPC 43**

**Table 3.2: Properties of cement**

Properties	Value	Specification (IS 8112:1989)
Grade of cement	OPC-43	OPC-43
Specific Gravity	3.14	3.10-3.25
Initial Setting Time	150 minutes	30 minutes (Min.)
Final Setting Time	385 minutes	600 minutes (Max.)
Normal Consistency	30%	-

### **FINE AGGREGATES**

Sand has been divided into 4 grading Zones according to IS: 383-1970 i.e. Zone I to IV. Natural river sand belonging to Zone II collected from supplier in Pathankot has been taken.



**Fig 3.5: Sieved fine aggregate passed through 2.36 mm**

Sand was sieved with IS Sieve 2.36 mm for this project due to the 2 cm selected size of the printing nozzle used in the 3-D printer developed. Higher size of aggregate could cause blockages in the nozzle. Table 3.3 shows the particle size gradation of aggregates

**Table 3.3: Sieve analysis of aggregates**

Sieve Size (mm)	Weight passing (kg)	% passing
0	0	0
0.15	1.17	9.375
0.3	6.86	54.97
0.6	8.96	71.79
1.18	10.78	86.37
2.36	12.48	100

### **FLY ASH**

Fly Ash is an important ingredient and widely accepted pozzolanic material as a cement substitution, which imparts long-term strength to concrete as amount of unhydrated cementitious material, increases which is used at later stages of hydration. Notably, the use of

fly ash reduces the carbon footprint of concrete. Table 3.4 shows chemical composition of fly ash.



**Fig 3.6: Fly ash**

**Table 3.4: chemical composition of fly ash.**

Constituents	Percentage (%)
$Al_2O_3$	39.95
$SiO_2$	57.40
$MgO$	0.33
$Na_2O$	0.10
$K_2O$	0.85
$FeO$	1.05
$CaO$	0.32

### **SILICA FUME**

Silica fume, a pozzolanic admixture also called micro silica is a by-product of silicon. It is used in the form of very fine powder having spherical particles. It imparts considerably high compressive strength and bond strength to Concrete. Composition of silica fume used is given in table 3.5

**Table 3.5: Chemical composition of Silica Fume**

Constituents	Percentage(%)
Al <sub>2</sub> O <sub>3</sub>	-
SiO <sub>2</sub>	99.78
MgO	0.11
Na <sub>2</sub> O	0.07
K <sub>2</sub> O	0.01
FeO	0.14
CaO	-



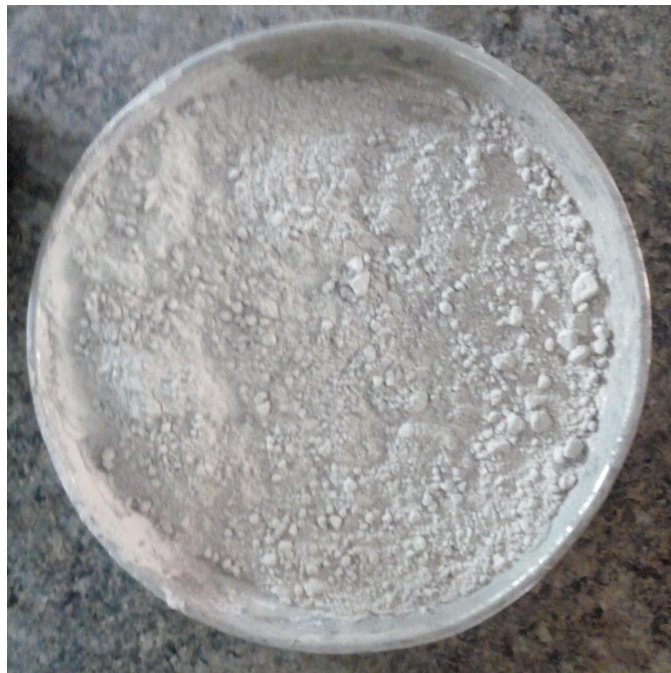
**Fig 3.7: Silica Fumes**

### **GROUND- GRANULATED BLAST FURNACE SLAG**

A by-product of furnace obtained by quenching molten slag in water, drying and crushing is glassy with granular shape and very less crystal formation. GGBS hydrates just like Portland cement and imparts high durability to concrete. Table 3.6 shows composition of GGBS used in this study.

**Table 3.6: Composition of GGBS**

Constituents	Percentage(%)
Al <sub>2</sub> O <sub>3</sub>	11.59
SiO <sub>2</sub>	35.34
MgO	8.04
Na <sub>2</sub> O	-
K <sub>2</sub> O	-
FeO	0.35
CaO	41.99



**Fig 3.8: GGBS**

### **SUPER PLASTICIZER**

Super plasticizers make concrete highly workable and reduce water content. Sika ViscoCrete 5207 NS was used as water reducing agent in the design mix. ViscoCrete 5207 NS is approved with IS: 9103-1999 and ASTM-C494. Properties of Sika Viscocrete 5207NS are shown in table 3.7.



**Fig 3.9: Sika Viscocrete 5207NS**

Advantages of Sika ViscoCrete 5207 NS:

- Very High water Reduction
- Improved flowability
- Improved strength and density
- Improved workability retention
- Improved rheology

**Table 3.7: Properties of Sika ViscoCrete 5207 NS**

Color	Light Brown
pH	6
Chemical Base	Poly carboxylate
Relative Density	1.12

## **WATER**

When water is added to concrete, binder undergoes hydration reaction that is responsible for strength of cement. Potable water is used for mixing and curing i.e. water used should be free from silt, oil or any organic matter. Tap water was employed in this research for both casting and curing purpose.

## **FIBRES**

Natural Polypropylene fibers were used in the mix design to impart strength and ductility to the mix. In printable concrete fibers imparts structural build up and helps concrete layers to

retain its shape. Normet TamFib MF 12. Fibers conforms to ASTM 1018 in conjugation with JSCE-S14.

**Table 3.8: Properties of Normet TamFib MF 12**

Color	White
Fiber length (mm)	12
Density	0.910
Tensile Strength	0.67 KN/mm <sup>2</sup>
Water absorption	Zero
Acid resistance	High



**Fig 3.10: Opened Fibers**

### **3.4 TESTS TO BE CONDUCTED**

For 3D printing of concrete, along with some basic properties of concrete some special tests to check its printability has to be performed. These tests have been discussed in this section.

#### **3.4.1 Extrudability**

The first thing that has to be seen while putting a material onto a printer is its ability to come out of it. This ability of concrete to flow out of a pump in the desired shape is called

extrudability of concrete. This property can be assessed by the distance over which concrete can be printed without any blockages in the nozzle. Another thing that has to be seen is the quality of the concrete paste printed by the pump. This can be evaluated by analyzing whether the concrete layer is without any gaps, cracks or segregation in the layer.

Extrudability was checked by extruding a 850mm continuous filament from the pump on an impervious surface. The extruded filament has to be without any deformity or cracks. The result of this test is defined by YES or NO. If this property of a material is satisfied only then material is considered for future evaluation.

### **3.4.2 Buildability**

In conventional methods, concrete is placed in molds, restricted by boundaries so this property doesn't play any role earlier. But in 3-D printing, layers are stacked above one another. These layers have a tendency to deform under the pressure of layers above. As this is a freeform method of construction and absence of lateral support to avoid expansion, concrete should have a tendency to sustain the load of layers that are built above with time. This property had been called buildability.

Buildability is defined as the number of layers of printing specimen which can be achieved without a collapse or deformation in any layer. In this research 3 layers were to be achieved for sample to pass the buildability test.

### **3.4.3 Flowability**

Concrete is stored in a container after mixing. Material has to be transported from the container to the nozzle through the pipe. Flowability of concrete comes into play to evaluate the smooth transfer of material. Slump flow test was performed in this research for measurement of flowability of concrete. Formulae 3.1 has been used to find the average slump flow of concrete.

$$D = (D_1 + D_2) / 2 \quad \text{[Eq 3.1]}$$

Concrete is put inside a frustum with base dia 300mm top dia 200mm and height of 100mm. Concrete is inserted in three layers and each layer is given 25 strokes with a tamping

rod. Excess of material has to struck off from top. When the slump cone is full, it has to be lifted from both sides and concrete is allowed to fall/ slump. The diameter of slumped concrete is measured, two readings are taken mutually perpendicular to each other. More is the diameter of slump, greater is the flowability.



**Fig 3.11: Slump Cone test**

#### **3.4.4 Shear Stress**

A robust rheological parameter, field shear vane apparatus (originally used for measuring shear strength of soils) was used to measure workability of concrete. This method was used because it derives relevant, scientific rheological parameter.



**Fig 3.12: Field Vane Shear apparatus**

A sample of fresh concrete is taken in the container, closed from one end and shear vane is lowered into the sample. Vane of dia 50mm and height 100 mm was used in this test. A constant rotation of 0.1°/s is applied and reading corresponding to the maximum value of torque reader is taken. The value of torque is used in equation 3.2 to get the value of shear strength.

$$S = T / \pi d^2 [(h/2) + (d/6)] \quad [3.2]$$

Where, d = diameter of vane (cm)

T = Torque applied in cm kgf-cm

h = height of the vane (cm)

S = Shear Strength in kgf/cm<sup>2</sup>

### 3.4.5 Open Time

This property has great relevance in concrete printing. Concrete sets with time that too speedily. So this gives a small window of time in which material is capable of printing. After a point of time, the shear stress in the material increases to an extent after which concrete cannot be printed.

This small window is represented by change of concrete stresses with time is called Open time. Open time is defined as the time period in which fresh concrete is printable. In this research, change in workability was associated with the open time, taking readings at an interval of 15 mins to the time period of one hour.

### 3.4.6 Initial Setting time

Setting time were found to have a generalized idea about the behavior of concrete and to study the effect of modified properties on the hydration reaction of concrete.

Vicat apparatus was used to find initial and final setting time of concrete. Concrete sample was taken in the circular mould and top is smoothed. Needle was attached to the vicat apparatus and was allowed to fall freely at an interval of two minutes. The time at which concrete failed to penetrate to 5-7mm from the plate was taken as initial setting time.



**Fig 3.13: Vicat Apparatus**

### **3.4.7 Compressive Strength**

Compressive Strength is perhaps the most important property of concrete. Concrete in any form used anywhere has to withstand some loads applied to it, perhaps it's not inaccurate to mention that the primary function of concrete is to sustain these loadings. This property of concrete is highly variable and needs to be evaluated irrespective of the type of concrete. Compressive strength is defined as the maximum stress that a material can resist under crush loading. Compressive strength is calculated simply by dividing the maximum load that concrete could take before failing by the original cross-sectional area of a specimen in a compression test.

Compression test in this research was performed on concrete samples with CTM Machine. Cubes of 150\*150\*150 mm were cast and cured. Specimens were placed between the plates with proper alignment. Load was applied by the machine automatically at a rate of 5KN/sec, load at which the sample breaks was considered for calculating compressive strength of the cubes. The compressive strength at 3 days, 7 days and 28 days were evaluated in this research.



**Fig 3.14: CTM used for compressive strength**

### **3.5 REFERENCE MIX DESIGN**

Following composition was used as a reference mix

Cement, aggregate, Ground- Granulated Blast furnace Slag, silica fume, fly ash, super plasticizer, fibers and water.

**Table 3.9: Reference Mix**

Material	Quantity (kg/m <sup>3</sup> of concrete)
Cement	612.5
Aggregate	1284
Silica Fumes	87.5
Fly ash	175
GGBS	-
Fibres	1.2

### **3.6 PRINTABILITY OF REFERENCE MIX**

The most important part of 3-D concrete printing is to make concrete pass through the system. Concrete is stiff material and shear stress are quite high, so it's difficult to pass concrete from a complex system and specially pipes where it can cause blockages. These blockages inside the machinery is most critical issue while printing concrete. This issue has been faced numerous times during this research in its preliminary testing and calibration stage. In addition, due to high stiffness and shear strength there is a lot of wear and tear in the machinery as a lot of friction and resistance is offered by concrete causing some damage to it. Therefore, the first property that had to be examined was extrudability. The smooth flow of concrete had to be made sure for starting the further investigation.

#### **3.6.1. Reconnaissance for Extrudability**

A 30 cm plastic container with 5cm diameter was taken. At one end, a cone was attached acting as a nozzle reducing the exit diameter to 2cm and at opposite end a cork was inserted sealing the container from the back flow of concrete when pressure is to be applied manually by the rod attached to the cork.

This method was adopted as a preliminary investigation before actually putting material into the pump as stiff concrete could easily cause blockages in machinery and clearing blockages is very time consuming or in some case parts had to be changed. To avoid this kind of problem a preliminary test was conducted on a much simpler apparatus, which could be cleaned easily, and a basic idea of concrete flowing through a 2cm nozzle could be examined.

For this test, a constant superplasticizer dosage was fixed at a little higher side i.e. 1% of binder and water content was varied in a wide range to get a minimum water-cement ratio. The minimum water cement ratio where the concrete becomes extrudable was selected,

#### **3.6.2. Extrudability and Buildability test with a centrifugal pump**

An air blower which has a centrifugal pump was modified, fabricated and calibrated then it was tested for reference mix with water-cement ratio selected from reconnaissance. Now the dosage of superplasticizer was varied by keeping the w/c ratio constant. Extrudability test was performed on mix with varying SP ratio. If a mix passed extrudability test then buildability test was performed on that mix, Pass and Fail results were computed.

If a concrete passes both extrudability and buildability test then it was considered printable. Further investigations were only to be done only if a concrete is pumpable, no failed mixes were considered as it was of no relevance to this research.

### 3.7 COMPARING PERFORMANCE OF DIFFERENCE MIX

In the reference mix, fly ash was substituted by GGBS by 5% in each mix reducing fly ash from 20% to 0%, i.e. fully replacing fly ash by GGBS. Flowability, Shear stress, open time, initial setting time, final setting time and 3 day, 7 day and 28 day compressive strength tests were performed on these 5 mixes.

**Table 3.10: Mix Designs (kg/m<sup>3</sup> of concrete)**

Material	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Cement	612.5	612.5	612.5	612.5	612.5
Aggregate	1284	1284	1284	1284	1284
Silica Fume	87.5	87.5	87.5	87.5	87.5
Fly ash	175	131.25	87.5	43.75	-
GGBS	-	1.2	87.5	131.25	175
Fibers	1.2	1.2	1.2	1.2	1.2
Water	253.75	253.75	253.75	253.75	253.75
SP	7.875	7.875	7.875	7.875	7.875

## Chapter 4

### RESULTS AND DISCUSSIONS

#### 4.1 Printability of Reference Mix:

Printability of reference mix was evaluated, superplasticizer dosage was fixed at 1% for initial trails. The amount of water in a mix was varied to find the optimum water-cement ratio. The minimum water-cement ratio where the mix was found to be extrudable was taken as the optimum water content. The extrudability results of mix with different water-cement ratios are stated as below.

**Table 4.1: Extrudability test of reference mix varying w/c ratio**

w/c ratio	Extrudability
0.48	bleeding
0.44	bleeding
0.40	bleeding
0.38	bleeding
0.36	bleeding
0.34	bleeding
0.32	bleeding
0.31	pass
0.30	pass
0.29	pass
0.28	fail
0.26	fail

When excess water was added in a mixture, there was segregation of aggregates that occurred in the mixture. When this mixture is filled in the container, the material in the lower region loses its water content and becomes stiff. Now this stiff material at the base of the container caused blockage of the nozzle and hence no material is extruded even when the concrete is highly workable. One of such mixtures has been shown in fig: 4.1. So, the water-cement ratio has to be reduced to a point at which the stiffening at the base doesn't happen, i.e. addition of SP and excess of water does not affect the rheology of the fresh concrete.



**Fig 4.1: Profile of an un-extruded material in the container**

Also, with high w/c ratio the strength of concrete decreases. The minimum w/c ratio is found at which the concrete is extrudable. Below a certain ratio, the workability of concrete so decreases that is anyway very stiff to be extrudable.



**Fig 4.2: (a) Un-Extruded Mix (b) Extruded Mix**

When the water content is decreases the rheology of concrete is improved the problem of blockages due to segregation of aggregates decreases. The material extruding at this stage is with gap and bulks as shown in fig 4.2 (a). At optimum content of water, extruded samples of mixture are found to be continuous without any bulking Fig 4.2 (b). When w/c ratio is decreased further, workability of concrete decreased increasing the stiffness of the material ultimately causing the blockages in the setup.

w/c ratio of 2.9 was found to be optimum for the reference mix. After the optimum w/c ratio was found, different dosage of super plasticizer were evaluated. This testing was done on the centrifugal pump. Minimum dosage required for mix to make it flowable enough to be pumped was selected. Excessive addition of superplasticizer could disturb the rheology of the mix concrete.

**Table: 4.2 Extrudability test of design mix with w/c= 0.29**

S.P. (%)	Extrudability
.5%	fail
0.6%	fail
0.7%	fail
0.8%	fail
0.9%	pass
1%	pass
1.1%	Not Buildable



**Fig 4.3 Extruded Filaments from 3-D Printer**

The SP ratio should be kept minimum as it affects the strength of the concrete. To find the SP dosage required a minimum dosage was given in mix and extrudability test was performed. The mix was found to be too stiff to be extruded. SP dosage was increased until a filament of 850 mm was extruded without any breaks. The material becomes extrudable at addition of 0.9% of SP as shown in fig 4.3.

Once an extruded filament is obtained, the next layer is laid over it and buildability test for the mix was performed. 3 layers were deposited to check the buildability of material. At low SP dosage the material, have shear stresses enough to resist the deformation of the base layer to sustain its own weight and the weight of subsequent layers that are deposited over it. As the SP dosage increases, there are deformations observed in the layers as shown in fig 4.4.



**Fig 4.4: Deformed layers**



**Fig 4.5: Un-deformed Layers (Buildable)**

The minimum SP dosage at which the material is extrudable has been determined and has been checked for buildability of layers. This ratio of w/c and SP dosage is said to be the optimum quantities to be added to concrete. At optimum proportions, a balance is maintained between the extrudability and buildability of the concrete, which is the major issue in the printable concrete. Fig 4.5 shows the optimum mix which is both extrudable as well as buildable.

The reference mix with w/c ratio of 0.29 and superplasticizer dosage 0.9% was found to be optimum for extrudability and buildability of concrete.

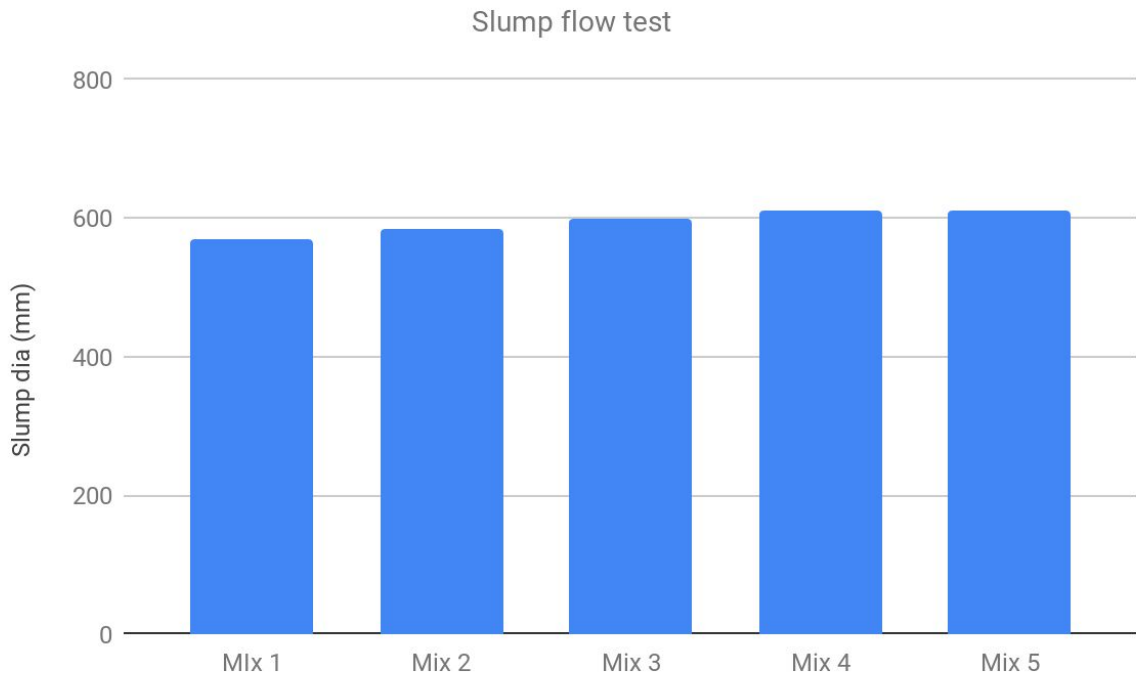
## **4.2 Comparing performance of concrete mix by substituting Fly ash with GGBS**

Fly ash in the concrete mix was substituted with GGBS in steps to 25% to complete replacement. Different parameters required for the printability of concrete were evaluated and were compared with the reference mix. Parameters that were evaluated were workability, open time, initial setting time, final setting time, Shear stresses and its variation with time and 3 day, 7 day and 28 day compressive strength.

### **4.2.1 Flowability**

Slump flow of all the mixes were taken at time  $t = \text{zero}$  and compared. The results have been shown in fig 5.1. It was observed that with the substitution of fly ash with GGBS, concrete

becomes more flowable although the variation in the value is small. High flowability of concrete corresponds to the higher extrudability of concrete. Mix 1 with 20% fly ash was found to be extrudable, so with the addition of GGBS flowability of concrete is improved.

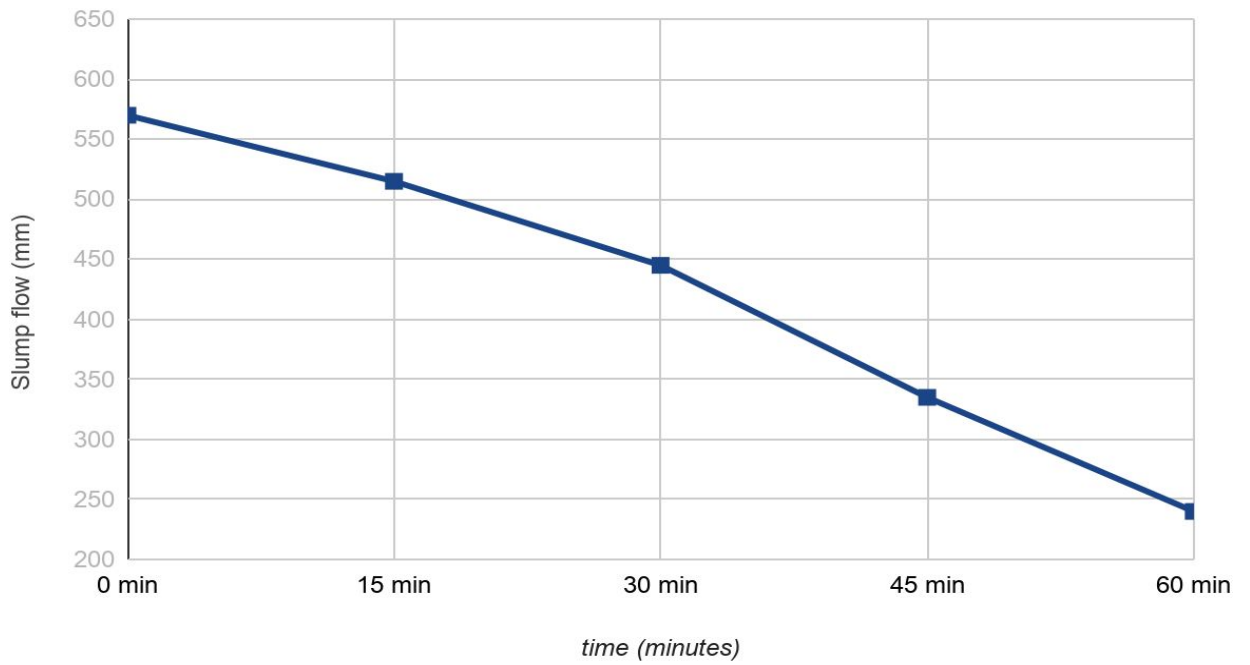


**Fig 4.6: comparison between slump flow values of different mix designs**

#### 4.2.2 Open Time

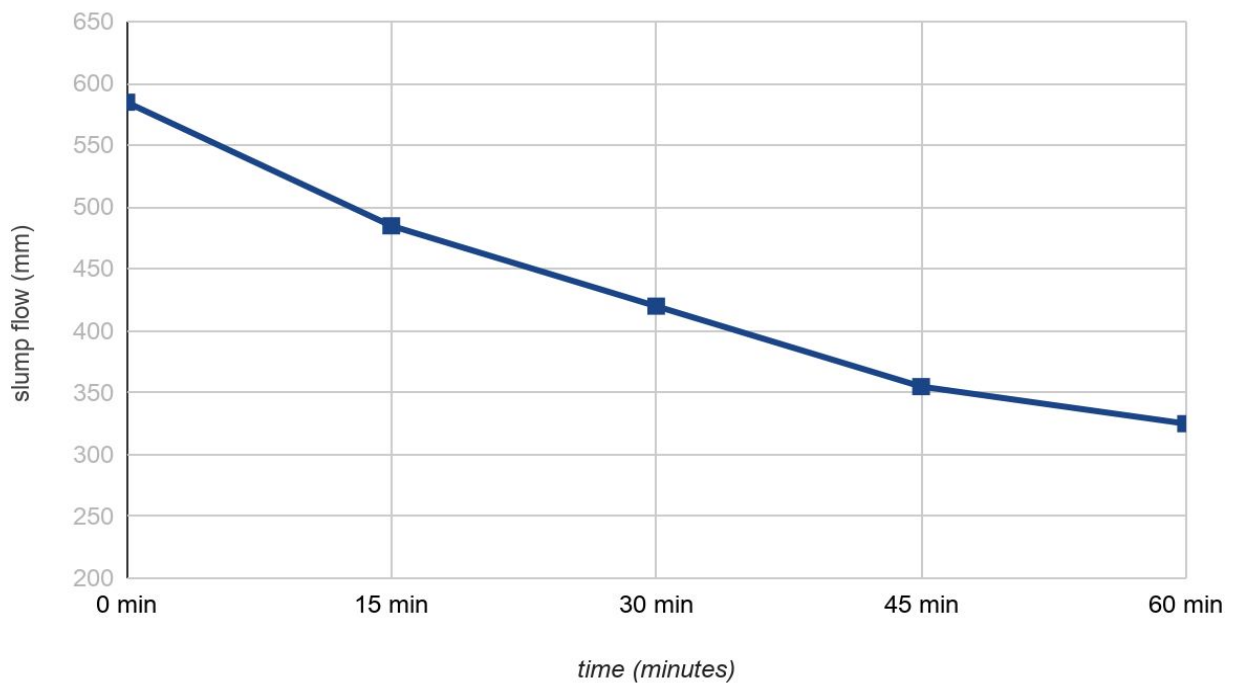
Open time was indicated with time period in which the concrete is flowable. Flowability results of mix designs at an interval of 15 minutes were taken and compared. With time, workability of concrete decreases and after a certain point of workability, concrete becomes non-extrudable. Concrete was found to be extrudable upto slump flow value 470mm [28].

Variation of slump observed in Mix 1 with 20% fly ash was very high i.e. workability of the mix is lost at a high rate. With the changing workability, extrudability of concrete is also affected. The open time of mix 1 was found to be less than 30 minutes, after which concrete was not extrudability.



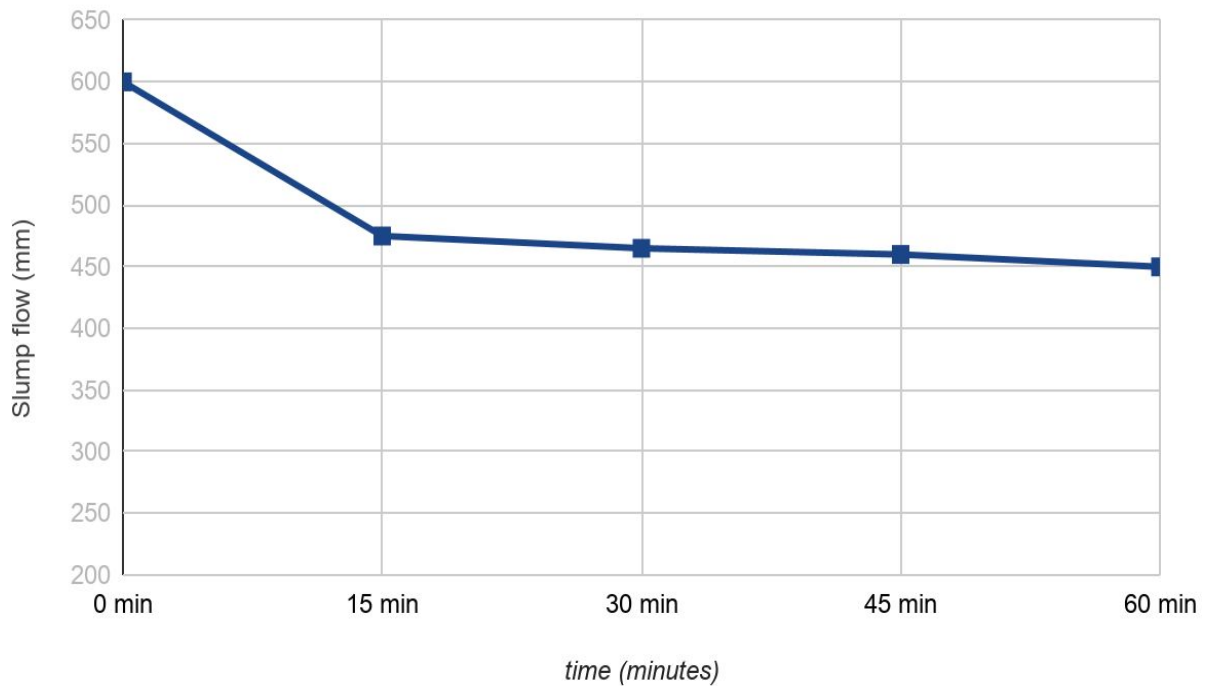
**Fig 4.7: Flowability of Mix 1 at different time intervals**

Slump value of mix 2 with 15% fly ash and 20 % GGBS showed some improvement as the workability at the 60 minutes. But the mix was still extrudable for less than 30 minutes so there was no considerable betterment of extrudability.



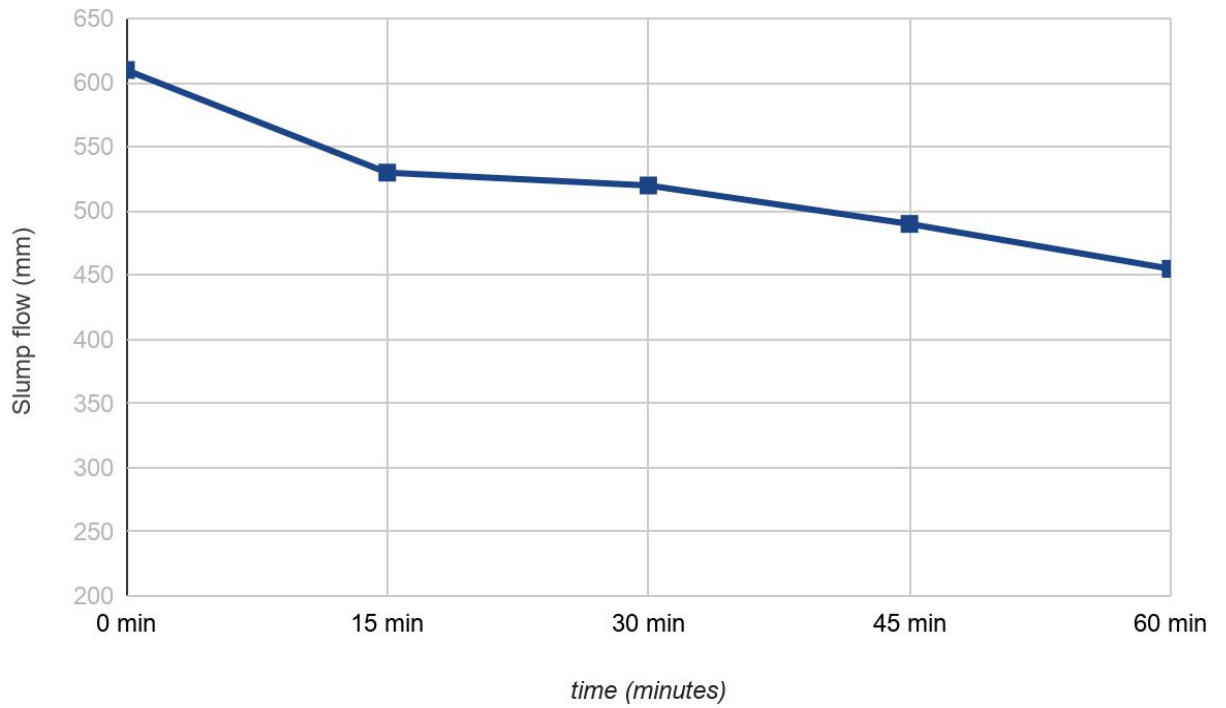
**Fig 4.8: Flowability of Mix 2 at different time intervals**

Mix 3 with 10% fly ash and 10% GGBS showed very less variation of slump flow after 15 minutes. Flowability remained almost constant and workability was significantly enhanced in this mix as compared to previous mix.

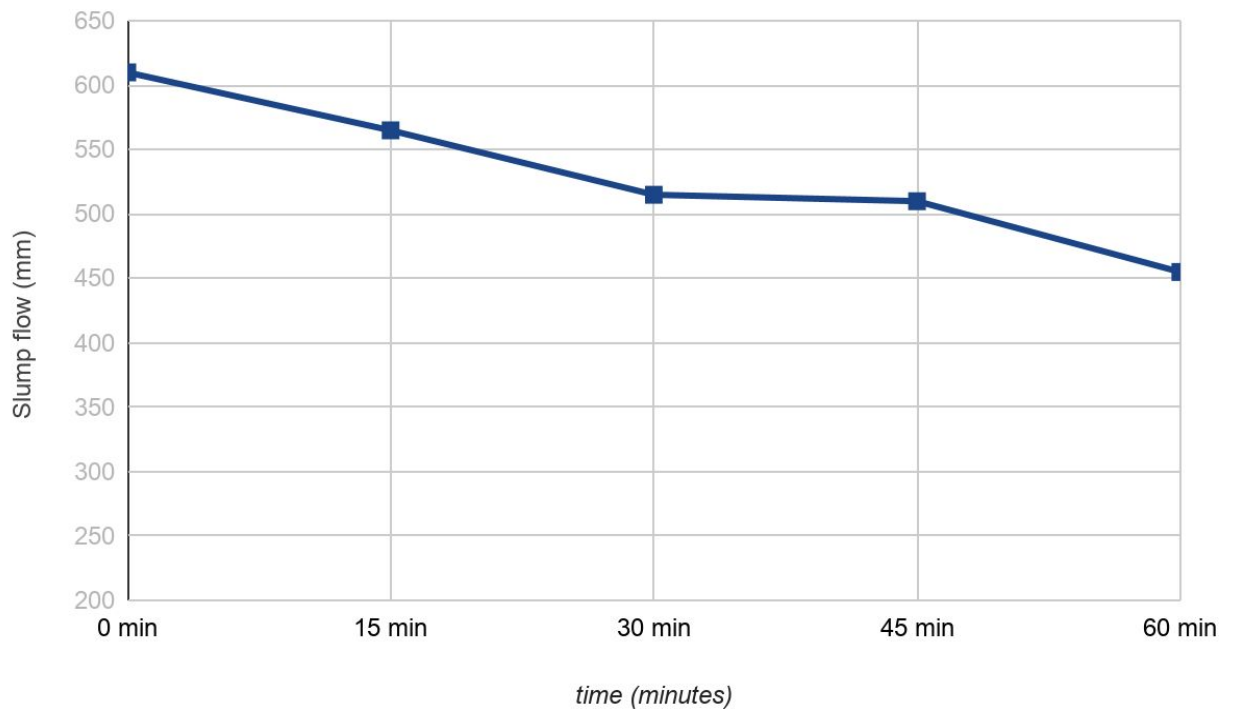


**Fig 5.9: Flowability of Mix 3 at different time intervals**

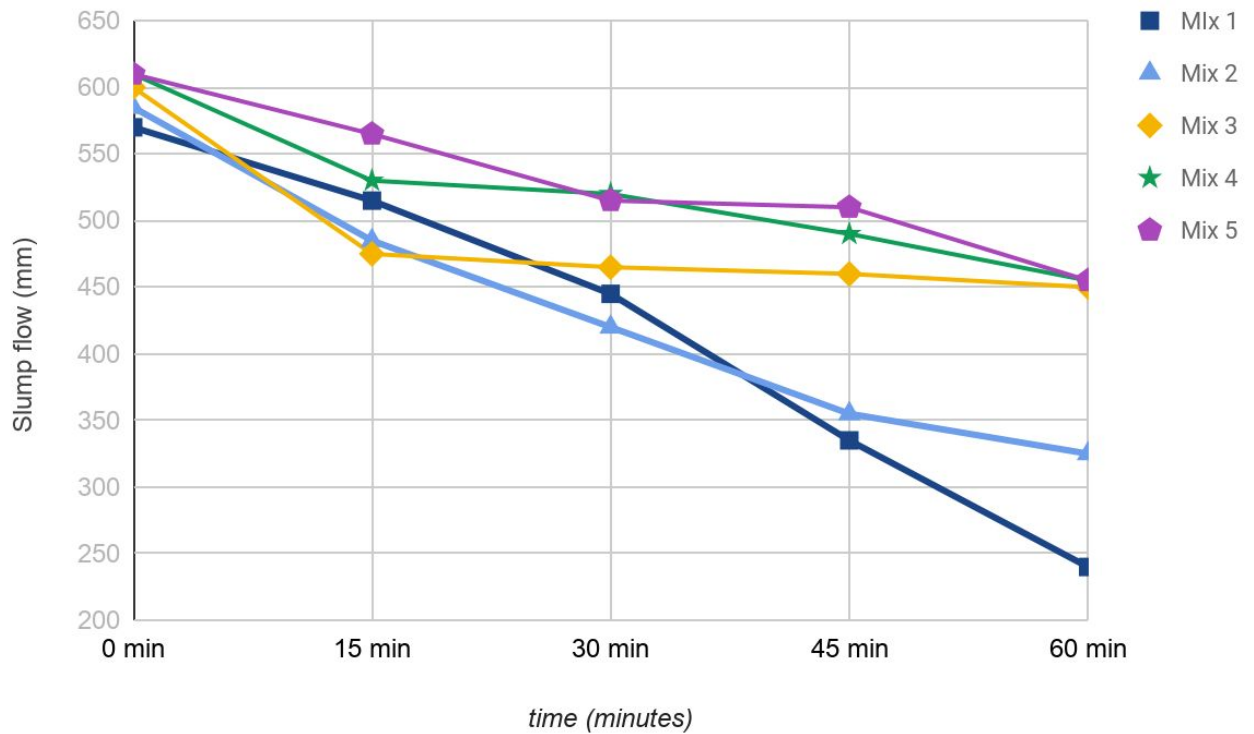
The open time was increased to more than 45 minutes in mix 4 and almost 60 minutes in mix 5. With high content of GGBS ( 15% and 20 % ) in the mix the open time of the concrete was doubled, from less than 30 mins to about 60 minutes.



**Fig 4.10: Flowability of Mix 4 at different time intervals**



**Fig 4.11: Flowability of Mix 5 at different time intervals**



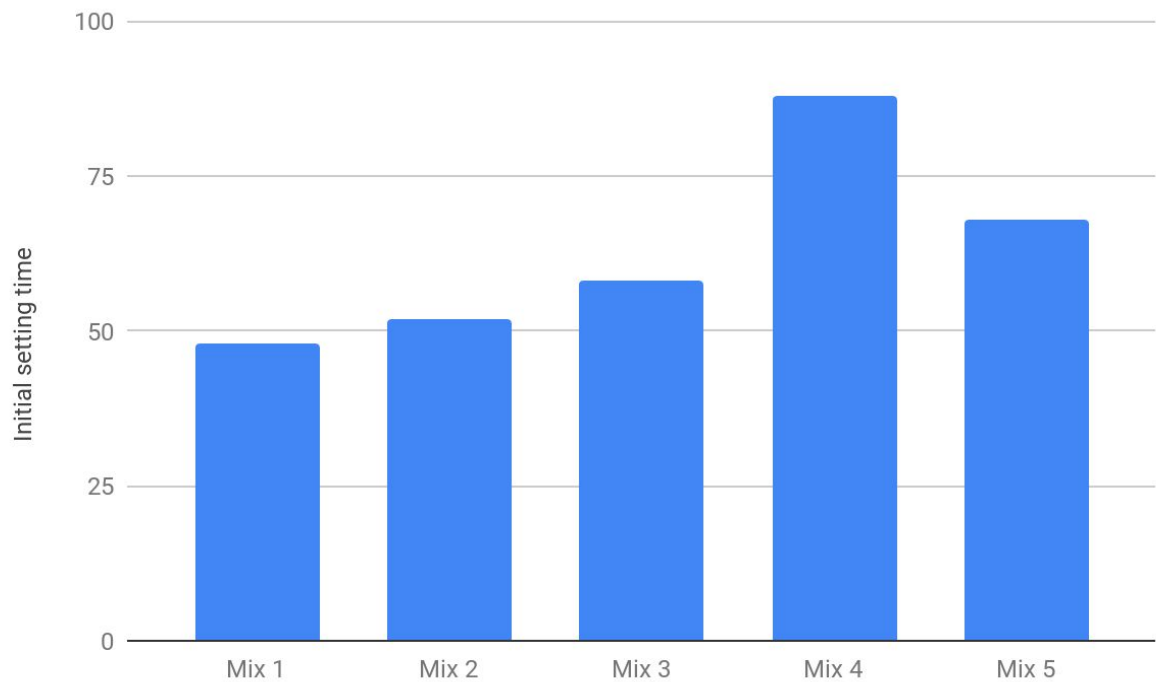
**Fig 4.12: Flowability results of all mixes at 4 rest times**

Mix designs with GGBS in it shows less variation in slump flow within 60 minutes of mixing. The open time was increased with substitution of FA with GGBS. The open time of printing concrete was increased from less than 30 minutes to about 60 minutes from mix1 to mix 5 with substitution of fly ash with GGBS. Due to this improvement in the open time, mixes in larger quantities can be prepared in single mixing, as it can be extrudable for long period without causing any blockages in the printer.

#### 4.2.3 Initial Setting Time

Initial time has been related with the inter bond strength of concrete layers [18]. The bond between the two fresh layers has to be strong for the structural integrity. After the mixing of water, the hydration reactions begins and concrete becomes stiffer with passage of time. Initial setting time is considered as the time until which the efficient bonds are built between the layers. The setting time was found to be low in mixtures with low GGPS content (0-10%) mix 1, mix 2 and mix 3, i.e. extruded layers form strong bonds within 50-60 mins of mixing. Whereas Mix 4 (15% GGBS, 5% fly ash) have exceptionally high initial setting time i.e. 88 minutes, due to which strong bonds could be formed and a high open time could be given. Even if the time gap is high between two layers, still bonds formed will be strong.

Also any uncontrollable delay would not affect the bond strength. Mix 5 (20% GGBS) shows open time of around 70 minutes



**Fig 4.13: Initial setting time**

#### 4.2.4 Shear Stresses

Shear stresses developed in fresh concrete gives the fair idea about the behavior of concrete as a fluid. As the layers of concrete are laid, the first layer shows some deformations. As numbers of layers printed increases, the load on the consequent layers beneath increases. This causes the collapse in the lower layers. So, the appropriate time at which the layer is stiff enough to retain the load of another layer above it is a critical parameter to know. Wrangler [29] showed that the stresses induced in the layer has the following relation [eq 4.1]

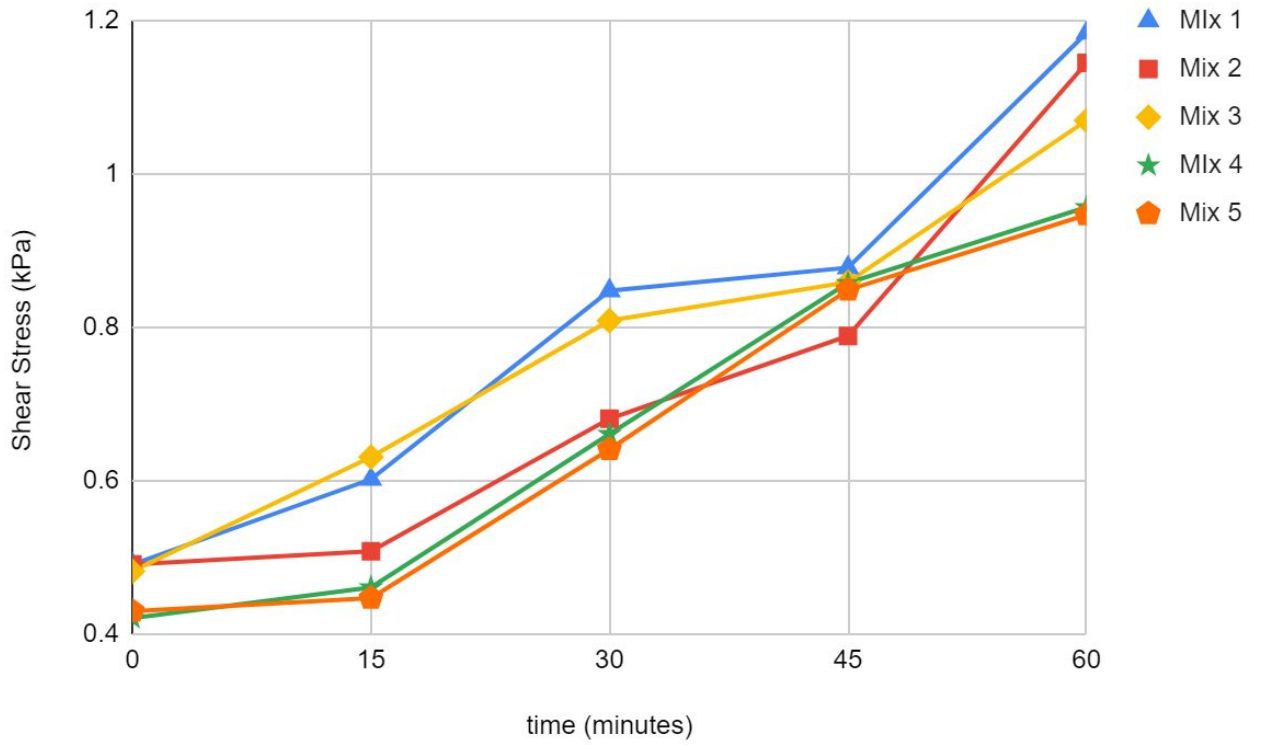
$$\tau_0 = \rho g H_m / \sqrt{3} \quad \text{[Eq 4.1]}$$

Where,  $\rho$  is density of concrete,  $g$  is the gravitational constant and  $H$  is the total height of layers. This shows the relation between the vertical loads applied on the layer with the shear stress, introducing a shape factor for the printed layer.

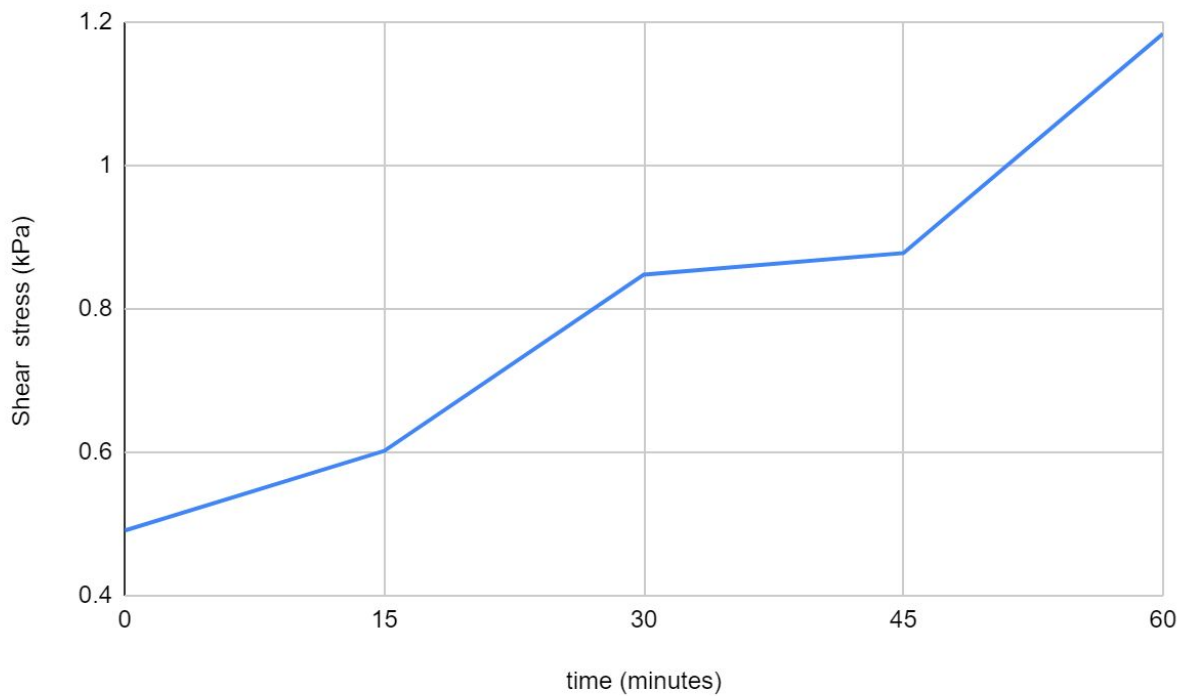
The first layer when extruded has to take its weight to retain itself and as the consecutive layers are laid over it, the lowest layer must have some shear strength to retain it. These values of shear stress are provided in table 4.3.

**Table 4.3: Shear stress required in the lowest layer to carry upper layers without deformations**

Number of layer	Shear stress required in lowest layer (kPa)
1	0.135
2	0.271
3	0.407
4	0.542
5	0.678
6	0.814
7	0.949
8	1.08

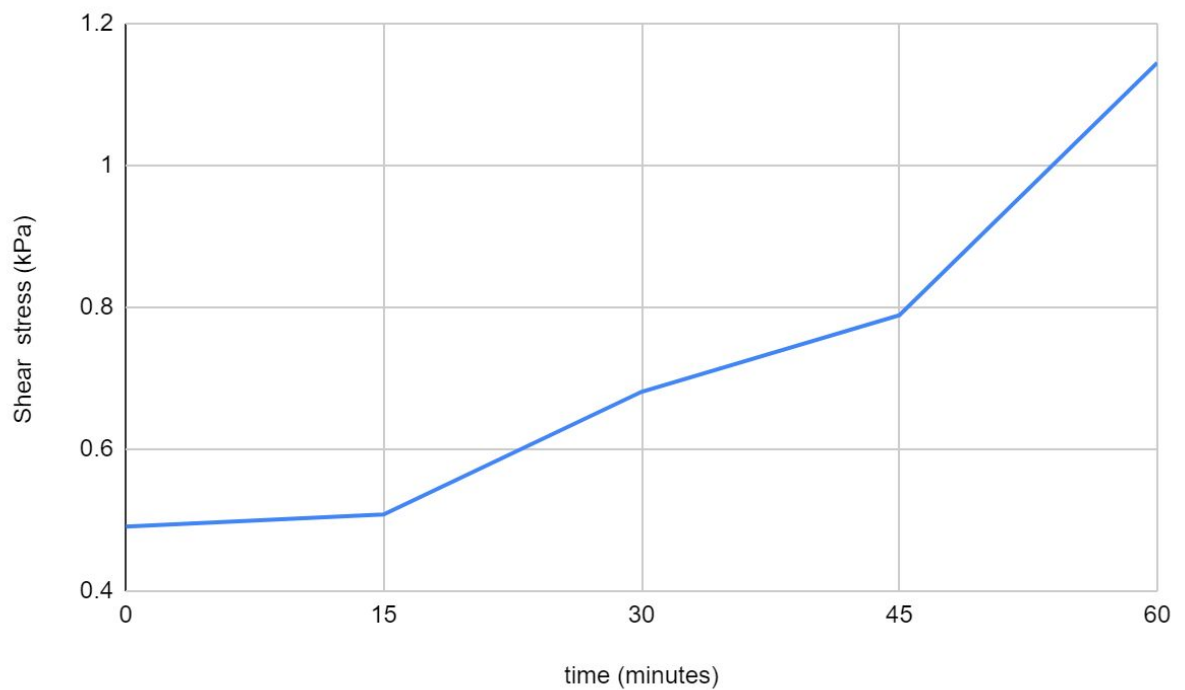


**Fig 4.14: Shear Stresses comparison of mixtures at 4 rest intervals**



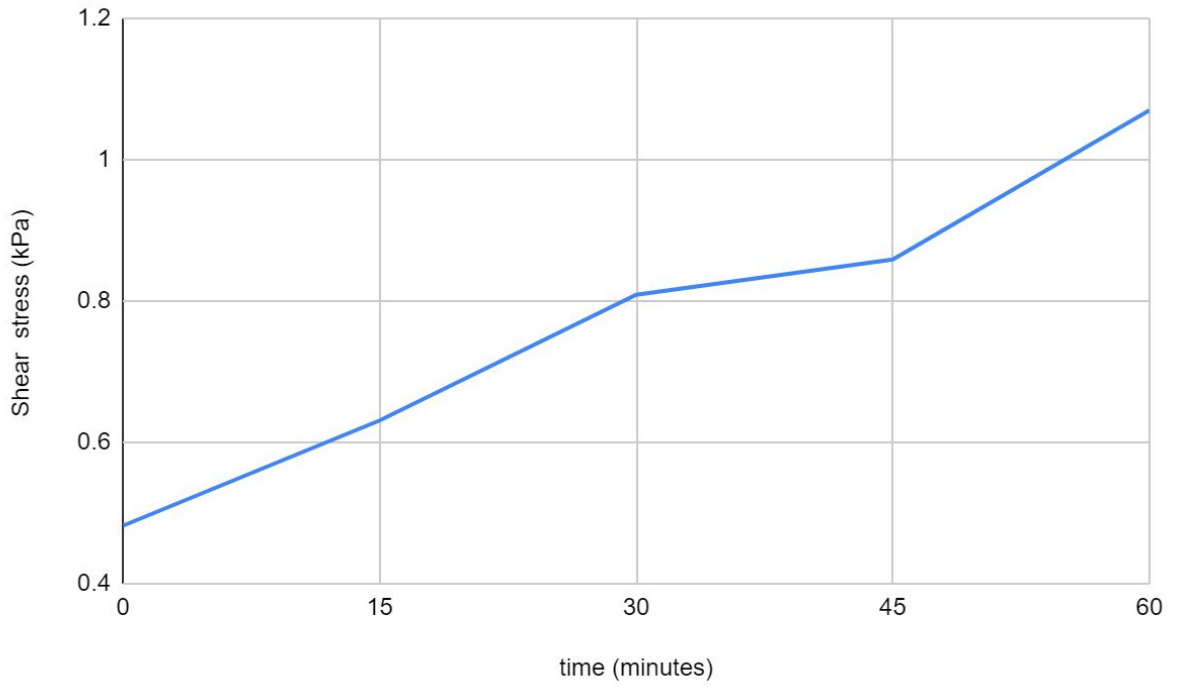
**Fig 4.15: Shear Stress in Mix 1 (20% fly ash) at 4 rest intervals**

Shear stress in the concrete mix 1(20% fly ash) are 0.491 kPa, which is enough to retain its own load. 3 layers can be built in the first 15 minutes, 2 more layers could be retained in the next 15 minutes. But no other layer can be laid in 30-45 minutes as the shear strength development is slow. Further two more layers could be retained by base layer in 45-60 minutes, making it able to retain total 8 layers in 60 minutes.



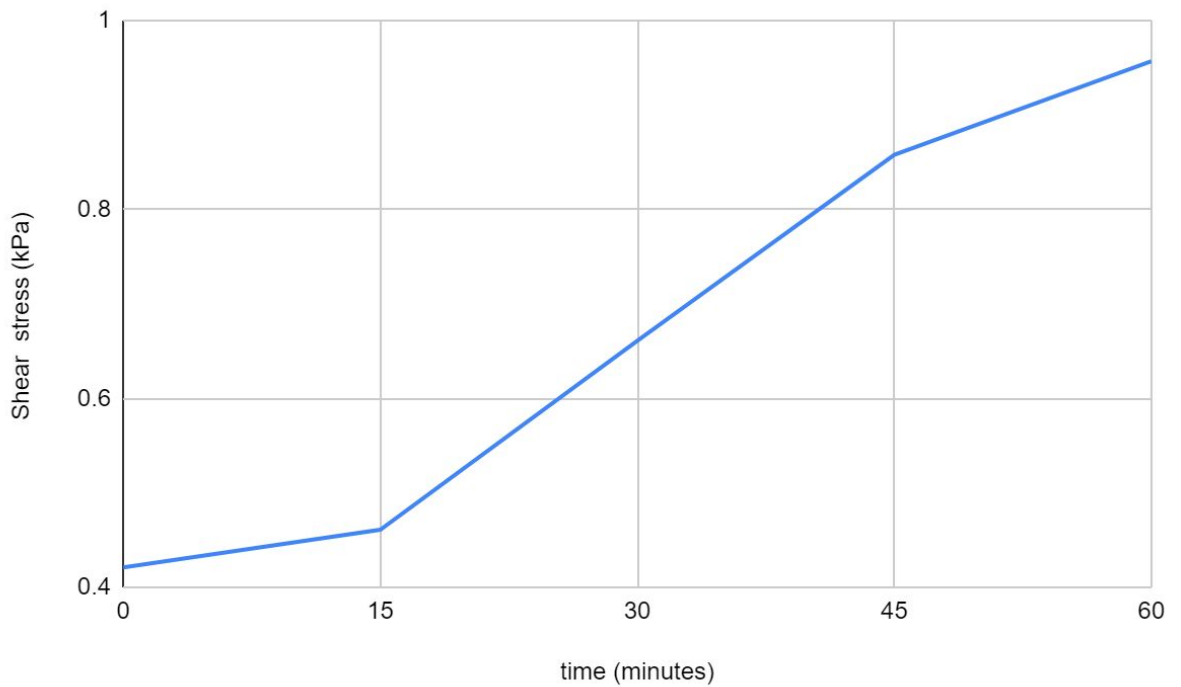
**Fig 4.16: Shear Stress in Mix 2 (15% fly ash, 5% GGBS) at different time intervals**

Shear stress behaviour of mix 2 (15% fly ash, 5% GGBS) was similar to mix 1, with printability of 3 layers in 15 minutes if mixing, 2 layers in the next 15 minutes. There was very little variation in shear stress from 30-45 minutes in mix 2 also and it cannot take more than 5 layers before 45 minutes. Three more layers could be retained from 45-60 minutes. 8 layers could be retained by mix 2 in 60 minutes.

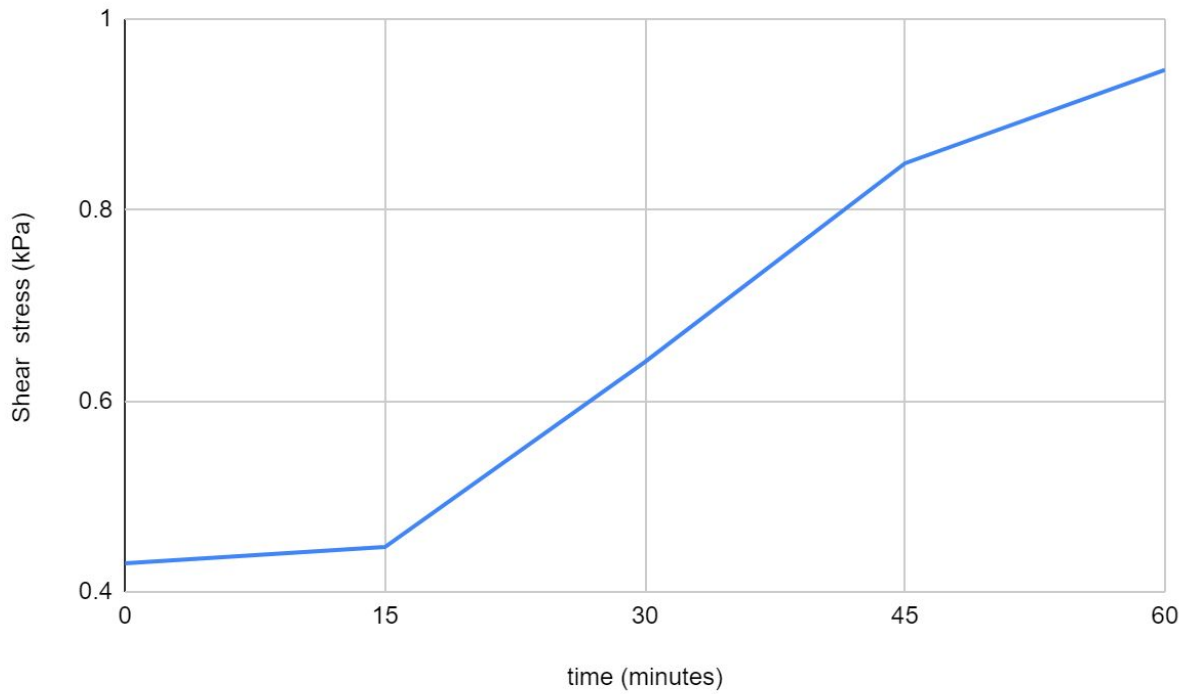


**Fig 4.17: Shear Stresses in Mix 3 (10% fly ash, 10% GGBS) at 4 rest times**

Mix 3 (10% fly ash, 10% GGBS) showed initial shear stress similar to mix 1 and mix 2. Four layers could be printed in the first 15 minutes of mixing, one layer each in the retained in next three intervals. Total seven layers can be built in 60 minutes with mix 3.



**Fig 4.18 Shear Stress in Mix 4 (5% fly ash, 15% GGBS) at different time intervals**



**Fig 4.19: Shear Stress in Mix 5 (20% GGBS) at 4 rest intervals**

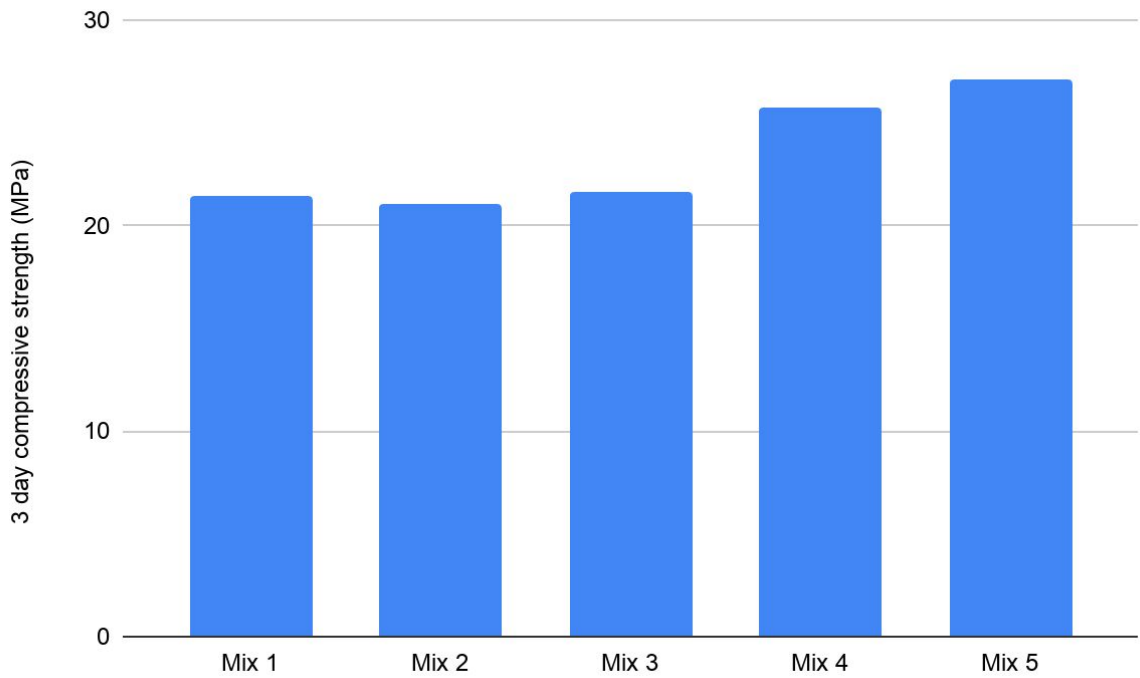
In Mix 5 (20% GGBS) Layers that can be laid without deformation in 0-15 minutes are 3, one in 15-30 minutes, two in 30-45 minutes and zero in 45-60 minutes.

The reduction in the number of printable layers with increased amount of GGBS in the mix in the first 60 minutes is due to the increase in the open time of printing. As the workability retention of the mix is increased with the Addition of GGBS, the hydration reaction is delayed delaying the strength formation of the paste. As comparatively low strength is attained in 60 minutes, the load bearing capacity of material is less resulting in a decrease of printable layers in one hours from 8 to 6 layers with 20% fly ash to 0% fly ash.

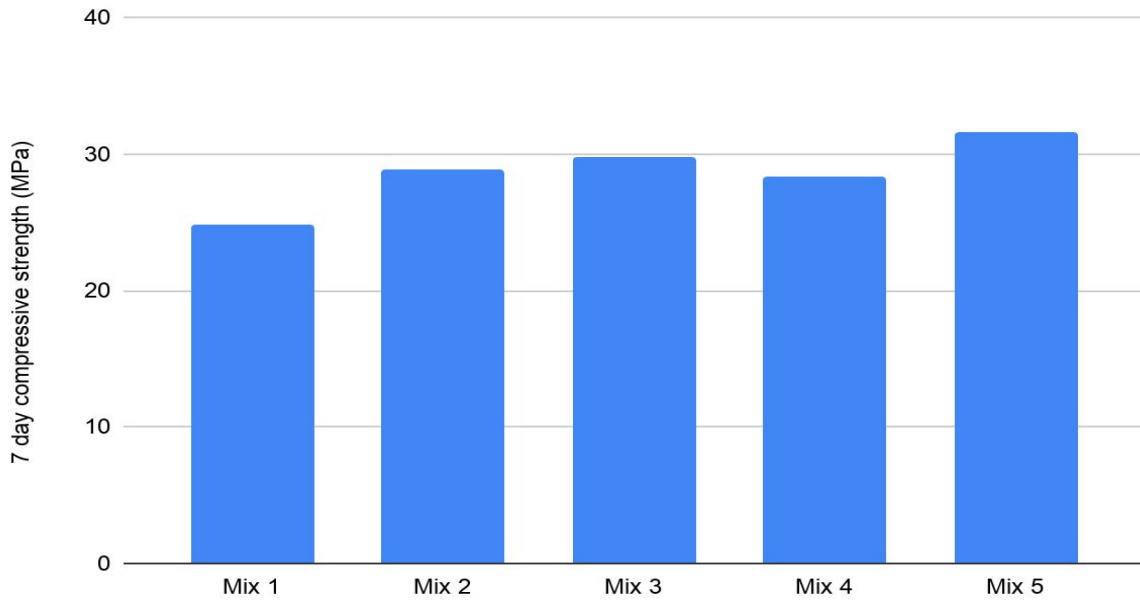
#### 4.2.5 Compressive Strength

Compressive strength of concrete is an important character and hence 3 day, 7 day and 28-day strength of concrete mixes had been found.

The strength attained by all the mixes in 3 days is similar 21MPa to 28 MPa. The rate of gain of strength is increased with the addition of GGBS as compared to the green concrete.

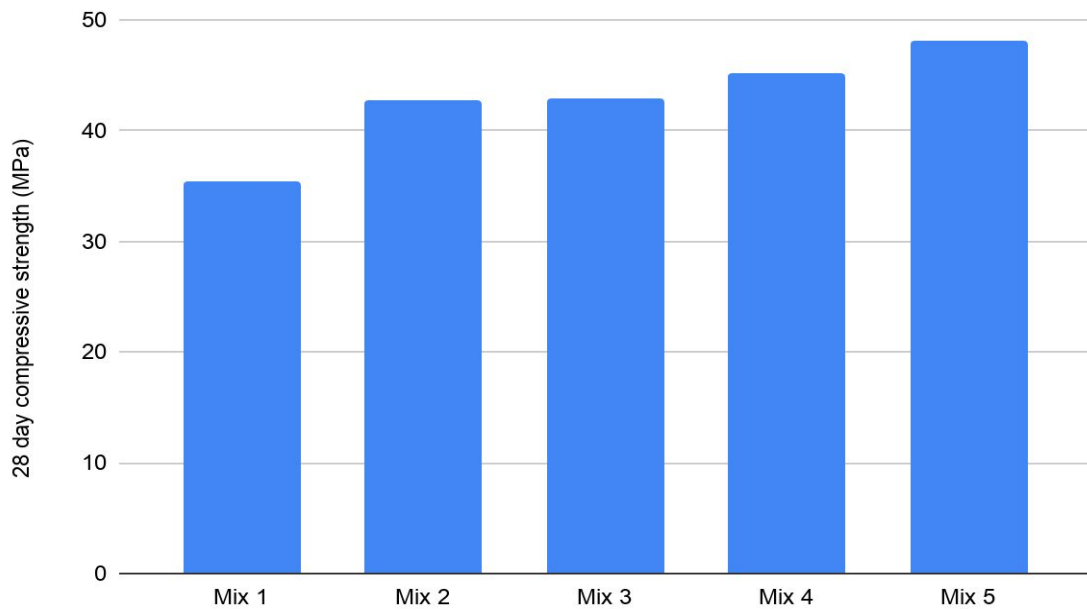


**Fig 4.20: 3 day compressive strength of 5 mixes**



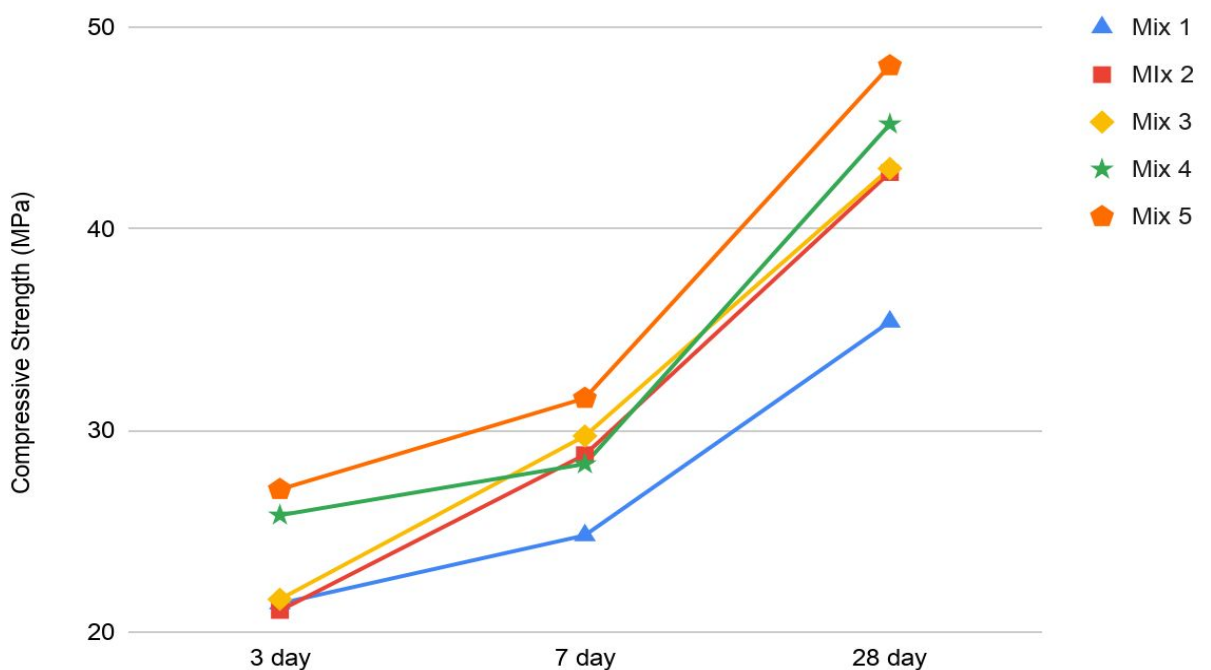
**Fig 4.21: 7 day compressive strength**

Similar trend is shown in 7-day strength of concrete. Mix 1 with 20% fly ash attains minimum strength and Mix 5 with (20%) GGBS gains maximum strength.



**Fig 4.22: 28 day compressive strength**

28-day strength of mixtures show considerable improvement in the strength of concrete with addition of GGBS to the mixture. The improvement in the compressive strength of concrete is 120% (5% GGBS), 122% (10% GGBS), 127% (15% GGBS) and 136% (20% GGBS).



**Fig 4.23: Comparative Compressive strength**

All 3-day, 7-day and 28-day indicates that with the addition of GGBS in concrete as a replacement of fly ash, compressive strength of mix increases.

The rate of strength gain is decreased in fresh concrete with addition of GGBS this is also due to the effect of superplasticizer added which allows the increased open time for printing. As the concrete gets hard, this rate is increased and at 28 days, improvement in compressive strength of concrete is observed.

The rate of strength gain can be seen in fig 4.23, which indicates the rate at which the strength of 5 mixes is increased. The increment in strength gain can be seen with the addition of GGBS.

## CHAPTER 5

### CONCLUSIONS

Mix 1 (20% fly ash) with water-cement ratio 0.29 and SP dosage of 0.9% passed extrudability test of printing 850mm of filament and buildability test of printing 3 subsequent layers. The speed of the frame was set at 17 mm/sec during the successful extrusion.

With 75% and 100% replacement of F.A in GGBS. Mix of 4 and mix of 5 shows maximum extrudability.

Mix 4 (15% GGBS) and Mix 5 (20% GGBS) gave maximum extrudability window of around 60 minutes in which a mix is extrudable. This extrudability is improved form less than 30 minutes with mix 1 (20% fly ash)

The open time of Mix 4 (15% GGBS and 5% fly ash) was found to be maximum with 88 minutes, so the higher time gap can be provided without affecting the bond strength of layers. Mix 5 (20% GGBS) have setting time of 72 minutes.

8 layers of mix 1 (20 % fly ash), mix 2 (15% fly ash and 5% GGBS) and mix 3 (10% fly ash and 10% GGBS) are buildable in 60 minutes. Whereas mix4 (5% fly ash and 15% GGBS) and mix5 (0% fly ash and 20% GGBS) can build 7 and 6 layers respectively in 60 minutes.

Compressive strengths of concrete are 35 MPa (20% fly ash and 0 % GGBS), 42 MPa (15% fly ash and 5% GGBS), 43 MPa (10% fly ash and 10% GGBS), 45 MPa (5% fly ash and 15% GGBS) and 48MPa (0% fly ash and 20% GGBS).

## REFERENCES

- [1] T. Bonwetsch, F. Gramazio, M. Kohler, Digitally Fabricating Non-Standardised Brick Walls, Paper presented at the ManuBuild conference proceedings, Rotterdam, 2007.
- [2] Shotcrete, <http://www.shotcrete.co.uk>.
- [3] Buildoffsite, <http://buildoffsite.org>.
- [4] Formtexx, <http://www.formtexx.com>
- [5] I. Agustí-Juan, G. Habert, Environmental design guidelines for digital fabrication, J. Clean. Prod. 142 ( (2017) 2780–2791.
- [6] I. Agustí-Juan, F. Müller, N. Hack, T. Wangler, G. Habert, Potential benefits of digital fabrication for complex structures: environmental assessment of a robotically fabricated concrete wall, J. Clean. Prod. 154 (2017) 330–340.
- [7] T.A.M. Salet, R.J.M. Wolfs, Potentials and challenges in 3D concrete printing, in: Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016).
- [8] B. Suhendro, Toward green concrete for better sustainable environment, Procedia Eng. 95 (2014) 305–320.
- [9] V.M.Malhotra, Making concrete "greener" with flyash, Concr.Int.21(1999)61–66
- [10] J. Pegna, Exploratory investigation of solid freeform construction, Automation in Construction Vol 5 (no. 5) (1997) 427–437.
- [11] B. Khoshnevis, D. Hwang, K. Yao, Z. Yeh, Mega-scale fabrication by contour crafting, International journal of Industrial and System Engineering Vol 1 (no. 3) (2006) 301–320.
- [12] Enrico Dini. “D\_Shape.”, <http://www.d-shape.com>.
- [13] S. Lim, T. Le, J. Webster, R. Buswell, S. Austin, A. Gibb, T. Thorpe, Fabricating construction components using layer manufacturing technology, (GICC'09), Paper presented at the Global Innovation in Construction Conference, Loughborough University, Leicestershire, UK, 2009, 13 -16 September, 2009.
- [14] Z-Corp. “Sls-Based 3d Printers.”, <http://www.zcorp.com/en/Products/3DPrinters/spage.aspx>
- [15] Peled A, Cyr MF, Shah SP. High content of fly ash (class f) in extruded cementitious composites. Materials Journal 2000;97(5):509–17.
- [16] Voigt T, Mbele JJ, Wang K, Shah SP. Using fly ash, clay, and fibers for simultaneous improvement of concrete green strength and consolidatability for slip-form pavement. Journal

- of Materials in Civil Engineering 2010;22(2):196–206.  
doi:10.1061/(ASCE)0899-1561(2010)22:2(196).
- [17] Tregger NA, Pakula ME, Shah SP. Influence of clays on the rheology of cement pastes. *Cement and concrete research* 2010;40(3):384-91.
- [18] Le, T.T., Austin, S.A., Lim, S., Buswell, R.A., Gibb, A.G.F. and Thorpe, T. (2012) Mix Design and Fresh Properties for High-Performance Printing Concrete. *Materials & Structures*, 45, 1221-1232. <https://doi.org/10.1617/s11527-012-9828-z>
- [19] Khayat, Kamal & Omran, Ahmed & Naji, Siwar & Billberg, Peter & Yahia, Ammar. (2012). Field-oriented test methods to evaluate structural build-up at rest of flowable mortar and concrete. *Materials and Structures*. <https://doi.org/10.1617/s11527-012-9856-8>.
- [20] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, R. Law, A.G.F. Gibb, T. Thorpe, Hardened properties of high-performance printing concrete, *Cement and Concrete Research*, Volume 42, Issue 3, 2012, ISSN 0008-8846, <https://doi.org/10.1016/j.cemconres.2011.12.003>.
- [21] Malaeb, Zeina & Hachem, Hussein & Tourbah, Adel & Maalouf, Toufic & El Zarwi, Nader & Hamzeh, Farook. (2015). 3D Concrete Printing: Machine and Mix Design. *International Journal of Civil Engineering and Technology*. 6. 14-22.
- [22] D. Lowke, D. Weger, K. Henke, D. Talke, S. Winter, C. Gehlen, 3D-Drucken von Betonbauteilen durch selektives Binden mit calciumsilikat basierten Zementen: Erste Ergebnisse zu betontechnologischen und verfahrenstechnischen Einflüssen, in: P.D.-I.H.-M. Ludwig (Ed.), *Tagungsbericht "19. Internationale Baustofftagung"*, Weimar, 2015.
- [24] Babak Zareian, Behrokh Khoshnevis, Interlayer adhesion and strength of structures in Contour Crafting - Effects of aggregate size, extrusion rate, and layer thickness, *Automation in Construction*, Volume 81, 2017,ISSN 0926-5805, <https://doi.org/10.1016/j.autcon.2017.06.013>.
- [25] R.A. Buswell, W.R. Leal de Silva, S.Z. Jones, J. Dirrenberger, 3D printing using concrete extrusion: A roadmap for research, *Cement and Concrete Research*, Volume 112, 2018, ISSN 0008-8846, <https://doi.org/10.1016/j.cemconres.2018.05.006>.
- [26] Lex Reiter, Timothy Wangler, Nicolas Roussel, Robert J. Flatt, The role of early age structural build-up in digital fabrication with concrete, *Cement and Concrete Research*, Volume 112, 2018, ISSN 0008-8846, <https://doi.org/10.1016/j.cemconres.2018.05.011>.
- [27] A.V. Rahul, Manu Santhanam, Hitesh Meena, Zimam Ghani, 3D printable concrete: Mixture design and test methods, *Cement and Concrete Composites*, Volume 97, 2019, ISSN 0958-9465, <https://doi.org/10.1016/j.cemconcomp.2018.12.014>.

- [28] Influence of rheology on the pumpability of mortar, COIN Project report no 21 Hedda Vikan and Stefan Jacobsen (NTNU)
- [29] Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., Bernhard, M., Dillenburger, B., Buchli, J., Roussel, N. and Flatt, R. (2016) “Digital Concrete: Opportunities and Challenges”, *RILEM Technical Letters*, 1, pp. 67-75. doi: 10.21809/rilemtechlett.2016.16.

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