3D Printable Concrete: Mixture Design, Simulation & Test Methods

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***Abstract*— Over the past decade, 3D concrete printing has shown tremendous potential in the field of construction industry especially in the field of residential projects. The fresh stage and hardened state requirements of 3D printable concrete are not controlled by the present codes and standards. Even though the conventional 3D printing with PLA, ABS etc. are becoming popular and accessible in common market, the concept of 3D concrete printing is still inaccessible even to the scholars and researchers due to the high cost involved. So, we need to develop a cost-effective methodology for experimenting and testing of 3D printable concrete mixes. In this paper, various historical data on mix design proportions are studied and a general conclusion is made so that how a more acceptable mix can be made with the locally available materials in the market with proper granular material packing. A software called Elkem Material Mix Analyzer is used for the optimization of the mix. The concept of Manual Extrusion (Manual 3D printing with hand held extruder) is introduced here for experiment purpose. Aspects of mixture compositions and their effects on properties especially on fresh stage and hardened stage of 3DPC are highlighted and mix design approaches are described. Presently we are following a trial-and-error approach, and which remains the norm. We have to develop a standard guide line to achieve design targets common to specific parameters of 3D printer and which should be universally acceptable.**

Keywords—3D printable concrete (3DPC), Rheological properties, Mix Design of printable concrete, Manual Extrusion, Material Mix Analyzer, Hand printing.

I. INTRODUCTION

In 3D printing the concept followed is additive manufacturing technique. Normally the structure is built layer by layer based on three-dimensional computer-generated model. Khoshnevis has invented the contour crafting technique, which is found as the major mile stone in this sector. 3D concrete printing is now found as an innovative technology that shows amazing potential with regard to the increase of safety and productivity in construction. The main economically feasible concrete printing methods are based on layered extrusion. So we can say that 3D printable concrete (3DPC) is a "tailor-made" material that can be delivered by the concrete mixer and pump and adjustable extrusion nozzle of a 3D printer. And then after deposition, it should maintain its shape stability under the gravitational load of already printed concrete layers above the printed layers without any support formwork. Compared to conventional concrete, 3DPC, as a keystone of a new, automatic, digital technology, brings numerous benefits to construction, like highly flexible architectural design, formwork-free fabrication, rapid construction, acceptable working conditions, material savings, etc. working conditions, material savings, etc. Cost efficiency also can be improved by this technology. Now the projects incorporating 3d printers are becoming recognized in the industry as an alternate technology in residential construction projects.3DPC has been successfully utilized in fabricating bridges, houses, bus stations, post offices and many other objects. Even though its rapid growing, we have only limited knowledge about this subject. For a successful extrusion process, the material must be flow able enough so that it can be extruded through the nozzle. But after the layer is extruded, the extruded layered concrete must have sufficient shear strength to resist deformation due to its superstructural weight & self-weight. Here thereby rheological parameters come in to play. The material must be fluid like with a low viscosity while inside the pump and nozzle, but once it's extruded out this should change to a solid like behavior with enough strength to resist deformation. With respect to the material used, so many approaches can be used for achieving this. We know that in 3D printing of polymers (e.g., poly lactic acid (PLA)), this is achieved by a sudden change in temperature. While inside the nozzle, the filament made with polymer is heated to above its melting point, then allowing it to flow through the nozzle. But once extruded, it is rapidly allowed to cool and causing a transition to a solid state. For concrete and other non-Newtonian yield stress fluids, the fundamental principle is far different. The pump applies enough stress to exceed the yield stress of the material, allowing it to flow and extrude through the nozzle end. After extrusion is done, the high yield stress allows the material to resist deformation and prevent flow in the material. Also, it is noticed that yield stress of the extruded concrete increases with time. Therefore, yield stress of concrete is identified as an important parameter for mixture design of 3DPC. A high yield stress is required to prevent deformation of extruded layers. Apart from this, if the yield stress and plastic viscosity become very high such that they exceed the capability of the pump, then extrusion of the material becomes fail. So, there is an optimum range of yield stress in which the material is both extrudable and buildable is found out by researchers. However, kindly note that this yield stress range is also dependent on the printer parameters. So, we need to develop a cost-effective methodology for experimenting and testing of 3D printable concrete mixes. Here empirical mix design method is studied and summarized the quantitative average measure of each ingredient of 3D concrete recipe, so that how a more acceptable mix can be made with the locally available materials in the market with proper granular material packing. A software called Elkem Material Mix Analyzer is used for the optimization of the mix. The concept of Manual Extrusion (Manual 3D printing with hand held extruder) is introduced here for experiment purpose. Along with this, for a particular set of print parameters used in the study, the optimum range of yield stress is determined for printable concrete.

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II. AIM

The main aim of this paper is a small effort to develop a cost-effective method for experimenting and testing of 3D printable concrete.

III. LITERATURE REVIEW

Literature review is conducted to understand about the mix design concept of conventional concrete and 3D Printable concrete. Also, this review addresses the yield stress-based mixture design approach for Portland cement-based concretes suitable for extrusion process.

A. Critical Review

By reviewing the literatures, it is identified as, the present codes and standards for conventional concrete can't be used for the 3D printable concrete mix design. Trial-and-error method identified as the norm, for finalizing the appropriate mix composition for 3D printable concrete. Researches on Existing Rheological models are still needed to develop them into reliable mix design tools. The currently available mix design for 3DPC mainly focuses on the printability of fresh concrete. The strength or durability characteristics of hardened concrete are not targeted mainly. Finite Element Method-based models can be used to simulate complex shapes and prints and could give printer parameter recommendations. Yield stress-based mixture design approach for Ordinary Portland cement-based concretes is suitable for extrusion process.

IV. METHODOLOGY

The topic was selected by understanding the potential of 3DPC, which in future can revolutionize the digital construction industry. For understanding the complexity involved in the production of 3DPC different journals were studied and literature review was prepared. Later participated in the workshop on advances in 3D concrete printing jointly organized by IIT Madras, IIT Hyderabad, Arizona State University dated 17th & 18th of March 2023, have brought light to the current status and road ahead of harnessing the full potential of this technology. There have been significant achievements with respect to the use of alternative cementitious binders and specialty admixtures, but several challenges still exist that come in the way of a large-scale adoption, such as reinforcement integration, alterations required in structural design, etc. Apart from this study is conducted on the basic 3D printers, 3D modelling, slicing & printing software used for conventional 3d printing. Different 3d printers and medias used for printing also studied. Gathered information regarding industrial practices, methods & technology innovations by discussing with COBOD, they are the global market leader in 3D concrete printing. Procedure adopted in 3D concrete printing by Indian startup TVASTA, Chennai is also studied from 3d modelling, slicing, printing simulation and up to the interface of 3d concrete printing with robotic arm printer named ‘R6’. Apart from this the initiative by ‘Minvayu Project’, Auroville Centre for Scientific Research, Tamil Nadu is really observed as inspirational. The budgetary 3D delta printer working on CURA open-source code is capable of printing sustainable clay & cement blocks. Inspired from all the above a Manual Extruder capable for executing testing 3DPC is made. Then Materials and ingredients required for the specified 3DPC mix is identified and procured. Reference mix is prepared. Tests for pumpability, Extrudability and buildability were executed. Necessary improvements / additions in Mix are suggested upon Test findings. Preparation of final Mix proportion. Then executed tests for Hardened Stage requirements.

The methodology adopted for this projected is described as follows:

a) Selection of topic

b) Literature review

c) Fixing of objectives

d) Study on 3D printing, 3D printers, process etc (Site visits, Workshops, FAB Labs)

e) The concept of manual 3D hand printing (making extruder)

f) Study & conclusion of 3DPC historical experimental data

g) Selection of raw materials

h) Optimizing the granular skeleton using EMMA

i) Onsite experiment – Trial-01 (Extrusion & Printing)

j) Modification of above mix (more sustainability approach) – Trial-02 (Extrusion & Printing)

k) Testing lab samples and printed samples.

A. Study on 3D softwares and 3D printers

All Additive Manufacturing (AM) system must start from a software model that fully detail about the external / internal geometry, this is inclusive of the use of almost any professional CAD solid modelling software, but the output must be a 3D solid model or surface representation. Now a days reverse engineering equipment like laser and optical scanning also are used to create this representation. Following are major 3d modelling software, slicing software and 3d printers used for development of 3D printing. 3D modeling software used are AutoCAD2020 & Fusion 360. Along with CAD modelling software we use Slicing software for 3D printers. A 3D slicer software is a 3D printer program where you can import 3D models into — for example. STL, GCODE or .OBJ file format. These models developed for 3D printers form the basis of the print. These files contain the geometrical information like details of edges, heights and all the information about your print. Following are the major slicing software under consideration. ULTIMAKER CURA (Open source), REPETIER, CREALITY CATALYST EX.

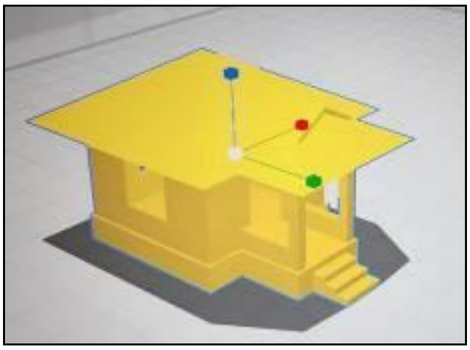

Fig - 1: STL File Imported in Slicer (CURA)

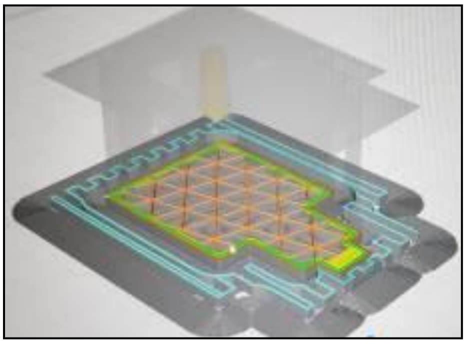

Fig -2: G- Code Generated – Print Preview & simulation in CURA

The types of additive manufacturing can be divided by what they produce or which type of material they use, but to apply structure to the technology worldwide, the International Standards Organization (ISO) divided them into seven general types, that we have already detailed in earlier chapters. Following are the major market leaders in conventional 3D printers which use PLA, ABS, PETG etc. for extrusion through fused deposition method. Major market leaders are STRATA SYS ENDER-3 V2 NEO ULTIMAKER.

B. Study on 3D concrete printers

Concrete 3D printers work in the same way as an Fused Deposition Method 3D printers. Both printers print layers over layers to create the final product. Here in place of a plastic filament, concrete 3D printers extrude specially designed concrete mixes. But, there are some differences, for concrete printing the printer is much larger. Printing a whole house or building need an industrial- sized gigantic printer. The other thing is the software program which will be an advanced version of the normal 3d printing software. Any 3D modeling software can be used to create the intended structure and then its is exported and programmed into the printer. After that the structure is printed either onsite or off-site and assembled at site.

Fig -3: India's Ist 3d Concrete printer at IIT Madras & India's Ist 3d Concrete printed structure at IIT Madras

Major types of concrete printing used in construction industry are classified in to two: gantry printer systems and robotic arm printer systems. Each method adopt different system to print 3D concrete.

Type 1: Gantry concrete 3D printers

The first system under study is gantry style printer. This is the most popular method out of the two. A gantry 3D concrete printer system consists of a printer extruder head that pivots from an x, y, and z-axis controlled automated gantry structural frame. The printer can move in following directions: up-down (z-axis), forward- backward (y-axis), and side-to-side (x-axis). An ideal example for this is the COBOD BOD2 printer from Denmark.

Fig -4: COBOD gantry type printer (BOD 2) & India's first 3D printed post office building at Bangalore made with COBOD printer, constructed by L & T. 1000sqft in 45 days, Crew of only 5 peoples. Cost 23 lakhs. Life span 50 to 100 years

Fig -5: India's first Industrial size 3d Concrete printer at IIT Madras by TVASTA & India's first 3D Printed house at IIT Madras (3DParts printed by Offsite printer, transported and assembled at site.)

Type 1: Gantry concrete 3D printers

The other type is robotic arm concrete 3D printing. Which is not as popular as gantry 3d concrete printer. It has got a moveable printer head like gantry printers, however, instead of moving around a defined space it has an arm-like structure that has got movement possible in all directions. They move between the x, y, and z planes, but they are more flexible than gantry and reach almost everywhere. A robotic arm then holds the extruder head and moves it around. Layering with concrete will continue until the project is finished. We have seen this in action with the TVASTA – R6 at their work shop at old Mahabalipuram road, Chennai.

Fig -6: TVASTA's robotic arm printer at TVASTA Factory at OMR – Chennai. Accelerator dosing pump can be seen on right side.

V. THE CONCEPT OF MANUAL 3D HAND PRINTING

Decades after the invention of conventional 3D printers, the extrusion materials changed from polymers to concrete, printers for 3D concrete extrusion are observed as unreachable to common researchers in India. The need for developing a Manual Extrusion mechanism is the first step to develop a cost-effective 3D printer that is affordable to common peoples. The above light weight and sturdy Extrusion system can be automated with a CNC machine.

In April 2019 L & T has hand printed first water tank of capacity at 2KL at Kanchi as a first step in to the 3D concrete printing industry.

Fig -7: L & T has hand printed first water tank of capacity 2KL at Kanchi in year 2019 & First Trial with COBOD printer in year 2022

Fig -8: Delta 3D printer at CUSAT, Kochi & Delta 3D concrete printer at Minvayu, Auroville

Mr. Jorge Ayarza of Minvayu Project, Auroville Centre for Scientific Research, Tamil Nadu along with his team has built cheapest 3D printer with locally available materials, which is running on open-source 3D printer slicing program called CURA. The shape and configuration of this printer is a larger version of DELTA printer which is used for prototyping with PLA/ABS. Which use low-cost controllers with external drivers and stepper motors.

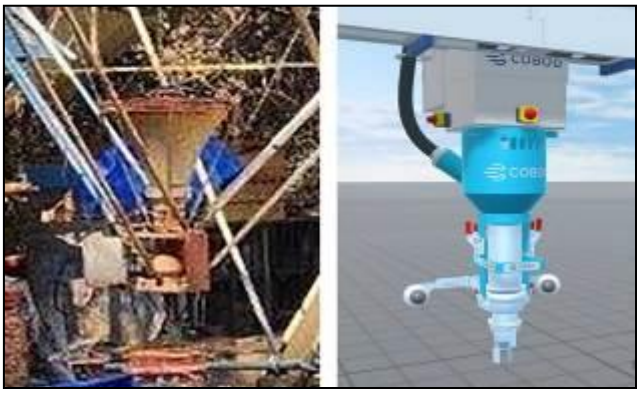

Fig -9: Extruder concept of Minvayu (Left) & COBOD (Right).

To Develop a Cost effective and accessible Methodology to simulate 3D Concrete printing process & Tests, the concept of Manuel 3D Hand Printing is introduced. The manual 3d extruder for hand printing is inspired from L& T's hand printed water tank and Extruder design of Minvayu & COBOD.

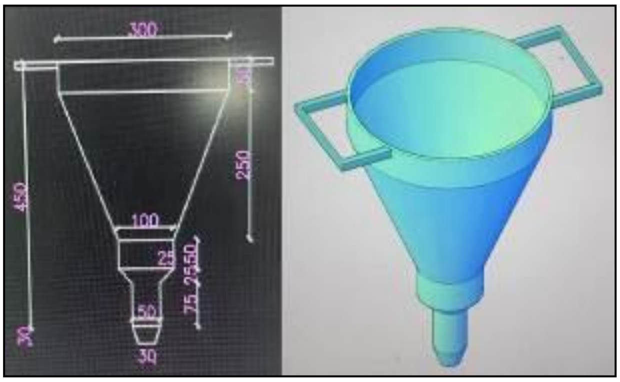

Fig -10: Concrete extruder for hand 3D printing: Conceptual drawing

Fig -11: Concrete extruder fabricated with available resources

VI. MIX DESIGN CONCEPT

The main issue of 3D printable concrete is the identification and selection of cost-effective raw materials and the proportioning & mix design to meet the pumpability, extrudability and buildability characteristics required for an effective 3D concrete printing. Apart from this the strength & durability targets are to be effectively controlled.

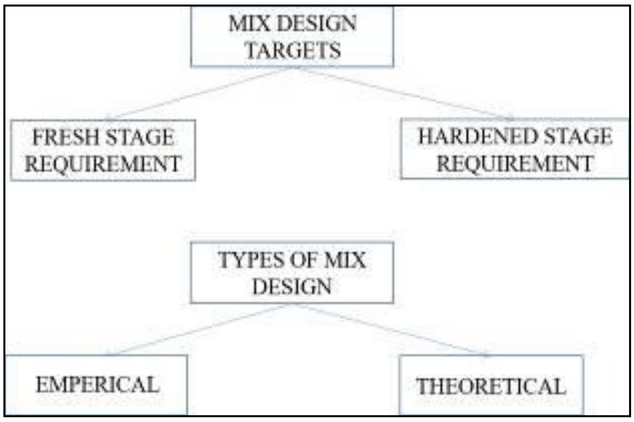

Fig -12: Mix Design Concept for 3DPC

VII. REFERENCE MIX DESIGN

Based on the calculation and analysis according to the statistical information in Fig. 10.2, the average mass proportions of aggregate, water, and binder are 53% ± 13%, 11% ± 5%, and 36% ± 10% respectively. If the density of 3DPC is assumed to be 2300 kg/m3, the average dosage of aggregate, water, and binder will be approximately 1220 ± 300 kg/m3, 250 ± 115 kg/m3, and 830 ± 230 kg/m3, respectively. It also can be calculated that the average water-to- binder ratio is about 0.3. In addition, Class F fly ash and silica fume are often employed as cementitious materials to partially replace cement.

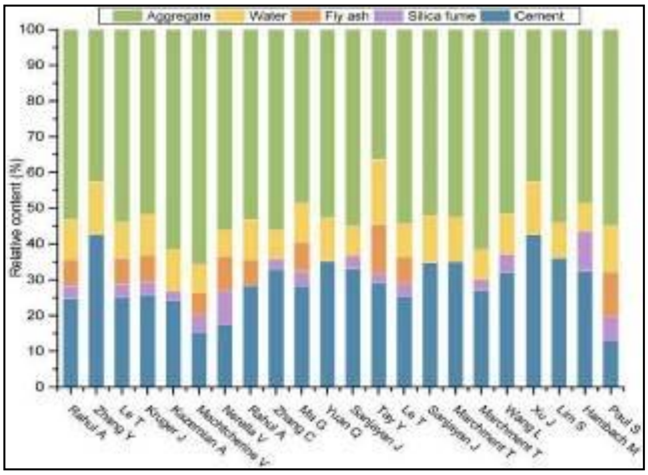

Fig -13: Relative content of binder, fly ash, silica fume, water, and aggregate in the optimum mixture proportion of 3DPCs

VIII. PROPOSED MIX DESIGN

We have made an analysis based on historical experimental data that is available in different journals and a conclusion on different percentage of constituents are made and tabulated as follows,

Table -1: Analysis of historical experimental data of 3DPC & proposed mix for hand 3D printing

Analysis of historical experimental data of 3dpc & proposed trial mix for hand 3d printing						
		Conclusion of historical experimental data (reference mix)		Trial - 01 for 3dpc		
		%	Tolerance (+or -) %		%	kg/m3
	Fine aggregate	53%	13%		51.8	1243
		Quarts powder max size 60microns to 1mm		Bharathapuzha river sand from Mayannur Palakkad (2.36mm to 150microns)		
	Water	11%	5%		11.05	265.2
Binder	Fly ash	36%	10%	ppc used (ultra tech)	10.98	256.89
	Silica				0	0
	Cement				23.83	571.8
	Water to binder ratio	0.3			0.32	
	Fly ash to binder ratio	20%			0.31	
	Silica fume to binder ratio	10%			0	
	Binder to aggregate	40:60			40:60	
	Granular skeleton optimization				by using EMMA - modified Andreassen	
	Distribution modulous (q)	0.25			0.28	
	Fibres	1.8kg/m3				
	Superplasticiser dosage. PCE based	0.10%			0.08%	
	Yield stress by vane shear test	1.6kpa				
	Time limit for printability	15min			10min	
	Additions to improve robustness					
	Nano clay (with sp dosage 0.13%)	0.30%				
	VMA (with sp dosage 0.18%)	0.10%				
	Silica fume (with sp dosage 0.18%)	10%				

A. *Stipulations for proportioning trial mix -01*

a) Grade designation: Importance given to Pumpability, Extrudability & Buildability. Targeting M40 and assumed 15% reduction in strength of printed samples.

b) Type of cement: PPC grade conforming to IS 1489 2015 part 1

c) Maximum nominal size of aggregate: 2.36 mm
d) Exposure conditions to be assumed as per Table 3 and Table 5 of IS 456: Severe (for 3DPC considered as reinforced concrete)
f) Workability: 140 mm (slump)
g) Method of concrete placing: Hand Printed by Manual Extrusion 3D Printer
h) Degree of supervision: Good
j) Type of aggregate: Crushed angular aggregate
k) Maximum cement (OPC) content: 450 kg/m3 as per IS456 cl: 8.2.4.2, but not applicable here
l)Chemical admixture type: Superplasticizer (Polycarboxylate ether based)

B. Material selection for trial mix -01

a) Fine Aggregate (Natural Sand) from Bharathapuzha, Mayannur, Ottapalam, Palakad
b) Cement: Ultra Tech Portland Pozzolana Cement (PPC- Fly ash based, Fly ash @ 31%)
c)Superplasticizer (Polycarboxylate ether based) Fosroc Auramix 400

C. Test data for materials

a) Cement used: PPC grade conforming to IS 1489 2015part 1
b) Specific gravity of cement: 2.9 (PPC)
c)Specific gravity
1)Fine aggregate (at SSD condition): 2.60
2)Fly ash: 2.50
3)Silica fume: NA
4)Chemical admixture: 1.11
d)Water absorption of Fine aggregate: 1.0%
e) Moisture content of Fine aggregate: Nil

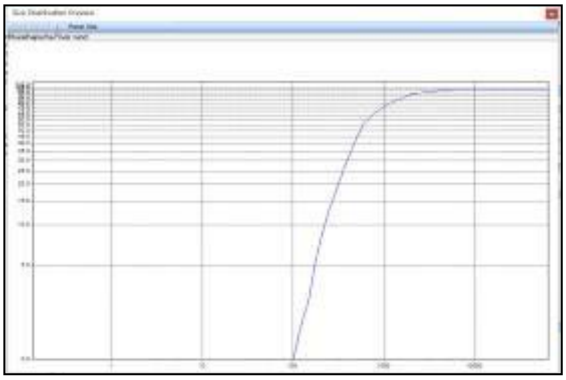

Fig -14: Particle size distribution curve for Bharatha puzha river sand

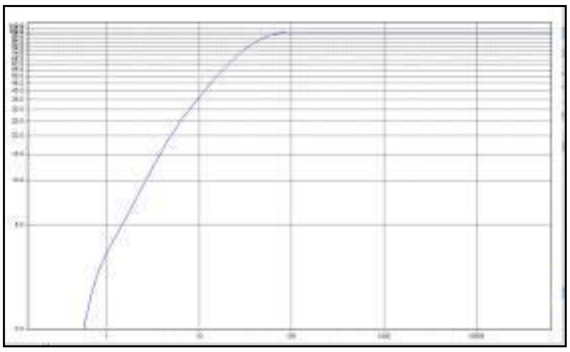

Fig -15: Particle size distribution curve for cement

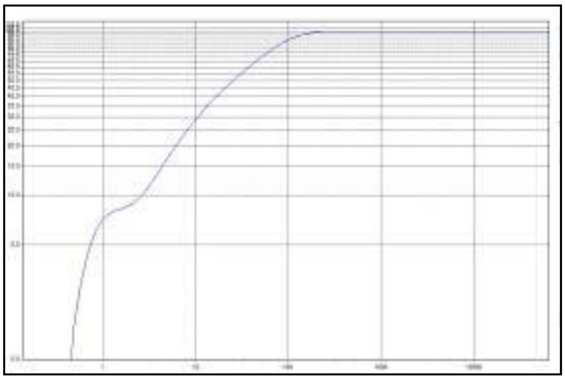

Fig -16: Particle size distribution curve for fly ash

D. Optimization of the concrete mix

Mix design for conventional mix is generally guided by IS456 and IS 10262 2009, which is updated on 2019. Irrespective of guidelines the method followed should satisfy the requirements targeted. Commonly the guidelines provide minimum cement content & maximum water cement ratio required for different environmental conditions like mild, moderate, severe, very severe and extreme. ACI 211 & EN 206 are the international standards on this. Mainly mix design targets workability & strength requirement. The modern concept of mix design is on Maximizing the packing of ingredients and minimize the paste. Optimization of granular ingredients like coarse aggregate, medium / fine aggregates, and cementitious binders. The mix design is then targeted to produce the amount of paste required over and above the void level in the granular packing. Along with the granular packing we may have to design the paste for best flow. Rheology deals with this. So, the yield stress (The minimum shear stress to initiate flow) & plastic viscosity comes in to play. In conventional mix design, proportion of coarse aggregate depends on zone of fine aggregate. In typical mix designs Zone II is used (Fineness increase from zone II to zone IV). For zone II determine coarse aggregate content. To attain a particular strength, determine the water cement ratio. With respect to maximum size of coarse aggregate determine water cement ratio. The modern concept of mix design is based on maximum density criteria.
In 1907 Fuller defined maximum density gradation.
$P_i = 100\,(d_i/D)^{0.45}$
Where Pi = Particle passing a particular sieve.
di = Specific sieve size
D = Maximum size of aggregate
In modern mixes more finer materials are using. This particle size distribution method considers the ad-infinitum concept of filler effect of supplementary cementitious materials (Size ranges from 20-40mm and to 150microns (sand), mineral admixtures less than 75microns, cement in between 10 to 15microns, silica fume less than 1micron. But too much of finer materials like silica fume etc will have negative impact to concrete mixes which is called loosening effect. There are few particles size distribution model software in the market, which are EMMA & EURO PACK.

The software uses a modification on above equation,

i.e., $CPFT = 100(d^q - dm^q) / (D^q - dm^q)$

CPFT = Cumulative percentage finer than

d^q = Particle size, dm^q = Minimum particle size

D^q = Maximum particle size, q = Distribution modulus (range from 0.21 to 0.37)

Here the proposed concrete mix is optimized by using 'Elkem Material Mixture Analyzer (EMMA)' and the granular structure is compacted to achieve more robust mix. Modified Andreassen model is used for Comparing the predicted particle size distribution of proposed mix. The 'q' value taken as 0.28. EMMA can be used for calculating the CO2 imprint of proposed mix. And which can give total energy spend in Kilo Jules on the production of concrete mix. Hence it can be used for sustainability impact analysis.

Fig -17: Optimization of mix by using EMMA

So, the particle packing approach can be suitably used to design special concrete like 3DPC. The use of this methodology leads to a reduction in the number of trials required to arrive at the mix design. The resultant concrete properties are affected positively. So cost effective concrete can be produced.

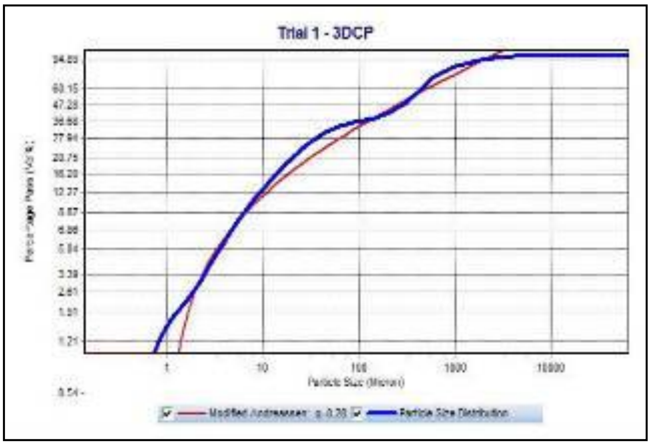

Fig -18: Output from EMMA - Particle size distribution of proposed mix (Blue colour) and Particle size distribution as per modified Andreassen model (Red colour)

E. Execution of trial mix-01 at lab

The different raw materials are weighed and mixed in a rotary drum mixture and the slump is observed as 140 mm.

Fig -19: Bharatha puzha sand for Trial Mix-01 weighed

Fig -20: Trial Mix-01: Materials Mixed consistency checked

Fig -21: Measurement of Slump (Slump value observed =140mm)

F. 3D hand printing with manual extruder

Here we are introducing a hand held manual 3d printer for experiment purpose. This aims to use the gravitational force along with augur agitation in extruder itself to facilitate the extrusion process. So, the optimum range of yield stress

ISSN: 2278-0181

determined for this manual extruded and printable concrete can be recorded for future references to achieve machine learning on FEM simulations to predict the buildability. The structural build-up with time is not assessed in these experiments.

Fig -22: Left - Material mixed in extruder, Right – Extrusion test & check admixture dosage

Fig -22: Extrusion by hand printer starts

Fig -24: Left – Check for buildability, Right - Hand printed sample

G. *Strength tests for trial mix-01*

The compressive strength of 150 mm x 150 mm x 150 mm cubes taken at 7 and 28 days

The laboratory samples made is cured in curing tank and printed sample kept open to facilitate actual site characteristics. The 3 sets of 150mmx150mmx150mm cubes taken is tested for 7 days compressive strength. Average Cube Compressive Strength obtained at 7days = 32.92N/mm^2.

Fig -25: Left – Compression test in progress

Fig -26: Cube crushed at 7 day & Cracking pattern studied

The 3 sets of 150mmx150mmx150mm cubes taken is tested for 28 days compressive strength.
Average Cube Compressive Strength obtained at 28days = 43.90N/mm^2
28day strength of onsite printed sample is taken by coring the specimen.

Fig -27: Cube crushed at 28day & Cracking pattern studied

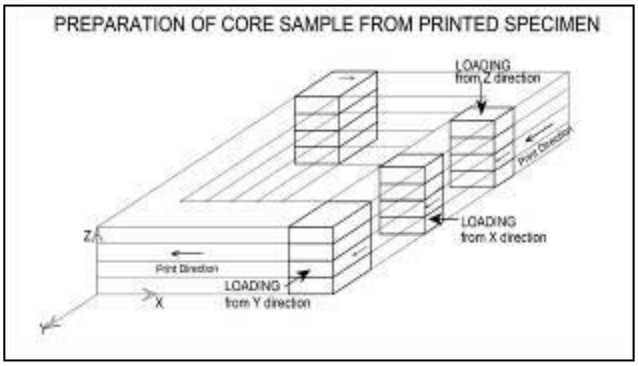

Fig -28: Diagram showing specimen preparation

Fig -29: Sample preparation in progress

The 3 x 3 sets of 60mmx60mmx60mm cubes core taken from printed sample and are tested for 28 days compressive strength. Cross and longitudinal cut sections examined to check voids, pores etc. Strong and hard surface texture found. No serious issues with inter layer bonding. The compressive strength is tested in X, Y & Z directions.

Fig -30: Core Samples taken. Print direction and top direction marked

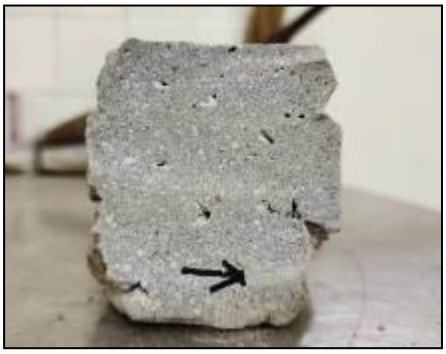

Fig -31: Core Samples cross section examination. No serious cold joints, shrinkage cracks or voids found

Fig -32: Enlarged view of core sample cross section: Strong and hard surface texture found. No serious issues with inter layer bonding.

$\alpha + \beta$

Fig -33: Onsite core samples were tested for compression:

Average Compressive Strength obtained at 28days along direction perpendicular to print direction and parallel to layers = 6.63N/mm^2 (X direction)

Average Compressive Strength obtained at 28days along direction opposite & parallel to print direction = 18.63N/mm^2 (Y direction)

Average Compressive Strength obtained at 28days along direction perpendicular to print direction and perpendicular to layers = 16.33N/mm^2 (Z direction)

IX. PROPOSED GREEN TRIAL MIX FOR HAND 3D PRINTING

The earlier made trial mix No:1 was having cement content more than 450 kg/m^3. A new mix design proposal is made with locally available sustainable materials, which is tabulated as follows.

Table -2: Proposed green trial mix for hand 3D printing

Proposed Green Trial Mix for Hand 3d Printing						
		Trial - 02 for 3dpc			Compare with trial - 01	
			%	Kg/m3	% as per trial 1	Wt as per trial 1
	Fine aggregate		51.8	1243	51.8	1243
		Bharathapuzha river sand from Mayannur Palakkad (2.36mm to 150microns)				
	Water		13.8	330.24	11.05	265.2
Binder	Fly ash	PPC used	9.7	232	10.98	256.89
	Rise husk ash		1.0	24.39	0	0
	Alccofine - 1203		3.0	73.17	0	0
	Cement		18.0	430.95	23.83	571.80
	Water to binder ratio		0.43		0.32	
	Fly ash to binder ratio		0.31		0.31	
	Alccofine to binder ratio		0.096		Not applicable	
	Binder to aggregate		37.96: 62.04		40:60	
	Granular skeleton optimization		By using EMMA - modified Andreassen		By using EMMA- modified Andreassen	
	Distribution modulus (q)		0.28		0.28	
	Fibers (raw rise husk) kg/m3		1.8		Not applicable	
	Superplasticizer dosage		0.19%		0.08%	
	Yield stress by vane shear test		1.9kpa		1.8kpa	
	Time limit for printability		14min		10min	
	Additions to improve robustness		Added nano clay only		Not applicable	
	Nano clay (with sp dosage 0.13%)		0.1% bentonite added		Not applicable	
	VMA, Silica fume					

A. *Stipulations for proportioning trial mix -01*

a) Grade designation: Importance given to Greening of the mix, Pumpability, Extrudability & Buildability. Targeting M40 and assumed 15% reduction in strength of printed samples.
b) Type of cement: PPC grade conforming to IS 1489 2015 part 1
c)Maximum nominal size of aggregate: 2.36 mm
d) Exposure conditions to be assumed as per Table 3 and Table 5 of IS 456: Severe (for 3DPC considered as reinforced concrete)
e) Workability: 140 mm (slump)
f) Method of concrete placing: Hand Printed by Manual Extrusion 3D Printer
g) Degree of supervision: Good
h) Type of aggregate: Crushed angular aggregate
i)Maximum cement (OPC) content: 450 kg/m3 as per IS456 cl: 8.2.4.2, Attempt to limit this within 450kg/m3
j) Rise Husk Ash as per IS 1727 1996
k) Alccofine 1203 as per IS 16715-2018
l)Chemical admixture type: Superplasticizer (Polycarboxylate ether based)

B. *Material selection for trial mix-02*

a) Fine Aggregate (Natural Sand) from Bharathapuzha, Mayannur, Ottapalam, Palakad
a) Cement: Ultra Tech Portland Pozzolana Cement (PPC- Fly ash based, Fly ash @ 31%)
b) ALCCOFINE – 1203, Micro Material
c)Rise Husk Ash
d)Superplasticizer (Polycarboxylate ether based) Fosroc Auramix 400
e) Raw Rise Husk
f) Kadukka Water
g) Jaggery Water

C. *Test data for materials*

a) Cement used: PPC grade conforming to IS 1489 2015part 1
b) Specific gravity of cement: 2.9 (PPC)
c)Specific gravity
1)Fine aggregate (at SSD condition): 2.60
2)Fly ash: 2.50
3)Alccofine: 2.85
4)Rise Husk Ash: 2.05
5)Chemical admixture: 1.11
d)Water absorption of Fine aggregate: 1.0%
e) Moisture content of Fine aggregate: Nil

Fig -34: Left - Kadukka (Terminalia chebula) water, Right - Jaggery water:

Fig -35: Rise husk ash:

Fig -36: Alccofine

Fig -37: Raw rise husk

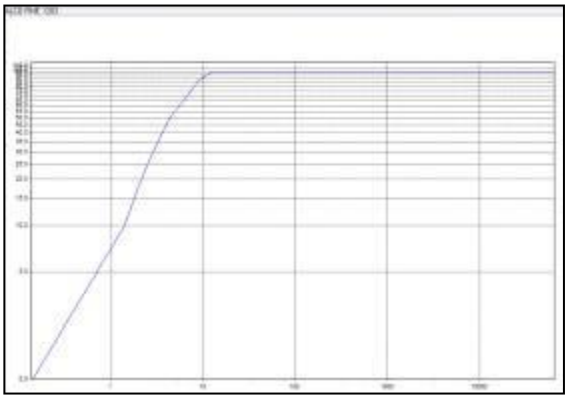

Fig -38: Particle size distribution curve for Alccofine

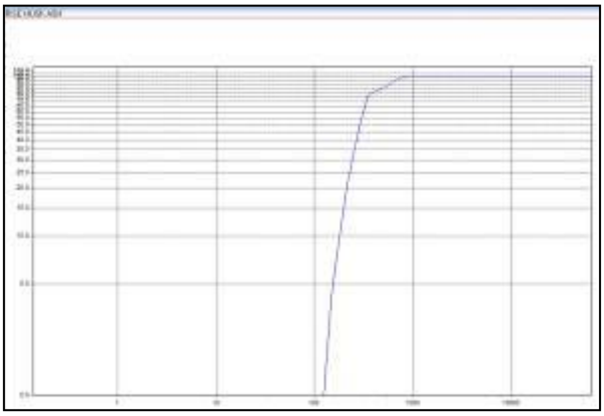

Fig -39: Particle size distribution curve for Rise husk ash

D. Optimization of the trial mix-02

Then the concrete mix is optimized by using 'Elkem Material Mixture Analyzer (EMMA)' and the granular structure is compacted to achieve more robust mix. Based on this we can predict the particle size distribution of proposed mix.

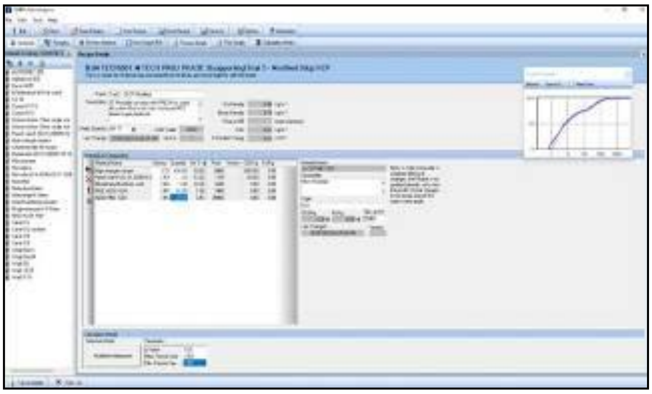

Fig -40: Optimization of trial mix-02 with EMMA

Fig -41: Particle size distribution of proposed modified green mix – Trial 02 (Blue color) and Particle size distribution as per modified Andreassen (Red color)

E. Execution of modified green concrete mix (trial mix-02)

Extrusion with trial mix No.2 is done satisfactorily and the buildability is found excellent with respect to trial mix No.1.

Fig -42: Extrusion process – Trial 02

Fig -43: Left - Extrusion completed & Right – Improved Buildability with respect to Trialmix-01

F. Strength tests

Strength test of trial mix No. 2 is done at 7 and 28 days. Average Cube Compressive Strength obtained at 7days = 5.1N/mm^2.
Average Cube Compressive Strength obtained at 28days = 7.30N/mm$^{2.}$
28day strength of onsite printed sample is taken by coring the specimen.

Fig -44: Core samples taken, print direction and top direction marked

Fig -45: Cross section examination. No serious cold joints, shrinkage cracks or voids found, chance of porosity

Fig -46: Enlarged section of Trial mix-02 sample: No cold joint, powdery surface texture.

Average Compressive Strength obtained at 28days along direction perpendicular to print direction and parallel to layers found negligible < 2.5N/mm^2 (X direction).
Average Compressive Strength obtained at 28days along direction opposite & parallel to print direction = 2.90N/mm^2 (Y direction).
Average Compressive Strength obtained at 28days along direction perpendicular to print direction and perpendicular found negligible < 2.5N/mm^2 (Z direction).

X. COMPARISON OF RESULTS

Trial mix-01 and Trial mix 02 are compared based on the type and quantity of ingredients used, easiness in extrusion and acceptability in terms of buildability when both the mixes are in fresh stage. We can see that the Trial mix-01 has consumed cement content of 571kg/m^3 whereas the reference mix taken as per historical data has taken cement content of 663kg/m^3. So, trial mix-01 has consumed 92 kg/m^3 less cement compared to reference mix design. Trial mix 01 use PPC directly instead of what is used in reference mix, where OPC and fly ash added separately. Trial mix-02 was an effort to make the 3DPC greener and more sustainable. Where the cement content is reduced to 430kg/m^3. In trial mix 02 admixture content along with water content has increased to make the mix more workable. The presence of rice husk ash and alccofine required the above increase to make the mix extrudable. It is observed that Trial mix-02 has more buildability compared to the trial mix-01. Whereas the compressive strength of Trial mix -01 found excellent and which is above 40N/mm$^{2.}$ But Trial mix-02 has shown very low compressive strength on laboratory cubes. Whereas the site core sample has shown reduction in strength of 57 to 85% of cube compressive strength. It is observed that the trial mix-01 can be used for load bearing wall construction as the lowest value taken from core samples is more than the requirement specified in IS2572-2005.

Table -3: Comparison of Trial mix-01 & Trial mix-02

Sl no	Properties	Trial mix-01	Trial mix-02	Reference mix
1	Total binder content	828.7 kg/m^3	760.51kg/m^3	828.7kg/m^3
2	Cement content	571.8 kg/m^3	430.95 kg/m^3	663kg/m^3
4	Type of cement	PPC	PPC	Cement & fly ash separately added
5	Other partial replacement for cement	No	Alccofine + rice husk ash	Silica fume
6	Fine aggregate content	1234 kg/m^3	1234 kg/m^3	1243kg/m^3
7	Admixture content	0.08%	0.19%	0.10%
8	Admixture type	PCE based	PCE based	PCE based
9	Water content	265.2 kg/m3	330.24	265.2kg/m3
10	Water to binder ratio	0.32	0.43	0.30

XI. CONCLUSION

As 3DPC printing process is far different from traditional casting, the mix designs for printable concrete were successfully tested with the help of a custom-made manual extruder.

The printable concrete workability requirements, like pumpability and extrudability is achieved by the addition of PCE based admixture. Whereas buildability is achieved by proper and compact gradation of ingredients. Addition of Fly ash improved the yield stress and buildability. Also, it enhanced the interlayer bond strength. Pozzolanic reaction favored reduction in shrinkage cracks. Even though techniques are available by using stiffeners / accelerators at the extrusion head for better buildability, the method adopted is by controlling the yield stress of the mix by proper gradation and PCE based admixtures.

This is a small effort to Establish a widely accepted Mix design concepts based on compressive strength and durability for printable concrete.

Even though the Trial-01 was made with PPC, we could able to reduce the cement content with respect to the reference mix design data available. Whereas general practice of the consumption of high-volume cementitious materials lead to high energy consumption and CO2 emission which does not accord with the principle of sustainable development.

So, effort was made to replace the cementitious materials with Rise Husk Ash and Alccofine along with PPC in Trial-02. Trial-02 was able to reduce the cement content within 450kg/m3. So, we can say that it is a green (sustainable) mix.

The modified mix design executed as Trial -02 was able to improve the buildability of the print.

But the strength performance of Trial-02 is not up to the expectations. Further fine tuning is required to attain the printability and strength characteristics of the green mix.

As sustainable construction practices are the ultimate Goal, further investigations are required for the development of 3DPC with coarse aggregate and low binder contents. Also, the use of LC3 Cement (Lime stone Calcined Clay Cement) will be able to save 50% clinker and save the resources available. Therefore, we can definitely say that, 3DPC is going to revolutionize the concept of low carbon lean construction. The tremendous efforts and researches in this area will change the future of construction.

ACKNOWLEDGMENT

We are expressing my gratitude to following persons for their technical support. Mrs. Manjusha Mathew (Assistant professor, MGMCET), Pampakuda, Dr. Manu Santhanam (IIT Madras), Dr. Radhakrishnan P.M (CUSAT CAD & 3D Printing Lab, Kochi), Mr. Jorge Ayarza (Minvayu Project, Auroville Centre for Scientific Research, Tamil Nadu), Mr. A.V Rahul (IIT Thirupathi), Mr. Vinod Eldo Baby (MACE Kothamamgalam), Mr. Paul Shaji (MACE Kothamangalam), Mr. M.A Joseph (Ultra Tech Cements Ltd), Mr. Shyju Nair (Treasurer, Indian Concrete Institute, Kochi), Mr. Parivarthan, Mr. Rohit, Mr. Tharun Sisodiya (TVASTA, Chennai), Mr. Roshin (COBOD, Asia Pacific, Malaysia), Mr. Minshad (CUSAT FAB Lab, Kochi), Mr. Bibin Raj (Lab Technician, Design Right Lab, Kochi), Mr. Salamon (FOSROC Ltd) Mr. Bhagyanath C, Mr. Sunny, Mr. Jayan K.V, Mr. Dileep T.A (Sargasala, Chendamangalam), Mrs. Simi Prajeesh (iBuild Care, Kottuvalli)

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