Experimental Investigation on Interlayer Bonding Strength of 3D Printed Concrete: A Review

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Abstract - *Concrete mix design is a multi-stage process in which we try to figure out what component combination is best for generating high-performance concrete. Modern literature, as well as cutting-edge corporate practice, provide concrete mix design approaches. The Three Equation Method-based techniques are the most widely used. Compressive strength is the most essential characteristics of concrete since it identifies the concrete class. The capacity to predict concrete compressive strength is critical for the use of concrete structures. The safety and durability qualities that are most essential to it. Machine learning has gotten a lot of press recently. And the technology's future prospects are far more promising. Machine learning algorithms have progressed to the point where they can discern patterns that people find difficult to spot. This has prompted interest in large-scale data mining. This is something we would discuss in our article. We wish to leverage state-of-the-art advances in machine learning algorithms for concrete mix design. During our inquiry, we gathered a big database of concrete recipes, as well as the harmful repercussions associated with them. We conducted laboratory testing to feed an artificial neural network with the best architecture we could find. The architecture of the artificial neural network has been turned into a mathematical equation that can be put to use in real-life situations.*

***Key Words*: 3DPC, Interlayer, Addictive Manufacturing, Concrete mix design, Digital construction, concrete**

1. INTRODUCTION

"This is a process of mixing materials to make objects from 3D model data, often layer by layer, as opposed to subtractive and formative manufacturing procedures." 3D printing, or additive manufacturing (AM), is commonly recognized as having enormous potential. In order to convert into one of these technologies, 3D printing has gotten a lot of attention from a variety of sources. There are television channels, newspapers, and internet services to choose from. What exactly is 3D printing, and how will it revolutionize the industry and put an end to traditional manufacturing as we know it? Policies in geopolitics, economics, social welfare, demographics, and the environment are developed and executed. What role does security play in our day-to-day lives? The fact that 3D printing is an additive manufacturing technology is its most basic and distinguishing feature. The additive manufacturing method. And since 3D printing is such a breakthrough technology, this is critical. This is unlike anything else I've ever seen: a revolutionary manufacturing process that assembles items utilizing contemporary technology, at a sub-millimeter scale, additively, in layers. Manufacturing methods that have been around for a long time are now being used.

Traditional molding manufacturing methods, including machining, casting, forming, and molding, have developed greatly through time, from manual to automated activities. Regardless, all of these processes require taking material from a larger block whether to generate the end product or a tool for casting or molding procedures and this is a major problem in the manufacturing process.

1.1 Connection of 3DPC

Concrete is frequently poured into a formwork, which acts as temporary structural support as well as a mold for molding the freshly set concrete to the desired shape and size. In most cases, the formwork is accompanied by a vibrating rod. Because the concrete has a shear-thinning effect, the tension created by the rod's vibrating motion removes air bubbles, increases compaction, and causes the material to flow in the formwork. This kind of manufacturing results inhomogeneous material with consistent strength throughout[1].

Although concrete 3D printing techniques offer a lot of promise, there are still a lot of technical concerns that need to be researched thoroughly. One such issue is the formation of so-called "cold joints" between printed layers due to weak interface strengths. Layer-to-layer interactions are inescapable due to the "layered" structure of 3D-printed objects. They are frequently the weakest connections in the overall structure[2].

The five phases of Portland cement hydration are the dissolution phase, induction period, acceleration period, deceleration period, and termination period. The hydration reaction at an early age is very severe. Within 24 hours, the response would usually have entered the deceleration or termination phase (h). The creation of paste structure during early-age hydration is intimately connected to the performance of set cement. In addition, the start and final setup times occur during the induction and acceleration phases, respectively. [3]

1.2 There are four phases to the overall 3D printing process and their concept.

1. 3D design
2. Slicing
3. 3D Printing
4. Post Processing.

Process

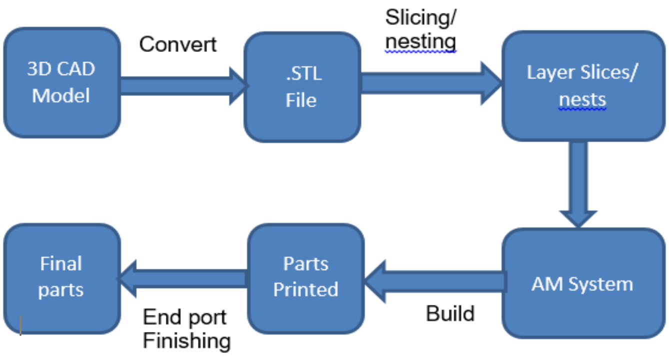
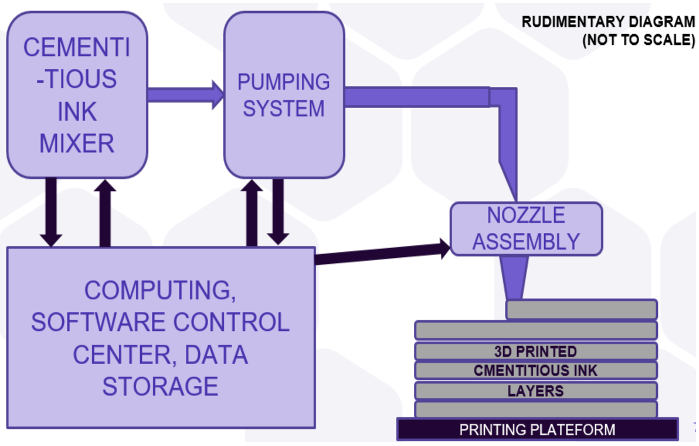


Fig-1 Flowchart of Process of 3D Printer Concrete

1.3Need of 3D Printed Concept

Concrete that has been 3D printed provides a number of advantages. The purpose of this study is to investigate methods for improving interlayer bonding strength. establish the safety of the 3D printed concrete building Achieve a high buildability and structural stability rate.



1.4 Objective of the study

The study's objectives are listed below:

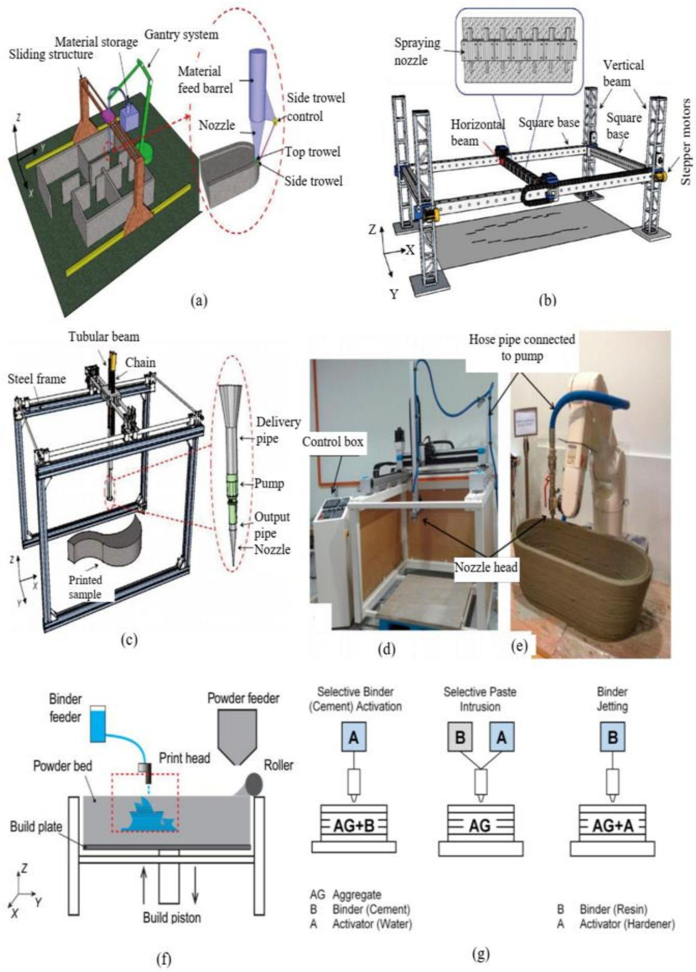
1.4.1 To identify and optimize an adhesive substance to improve the interlayer bonding strength between two mortar layers

1.4.2 To understand the process of ASR and devise a method to decrease it in 3DPC.

1.5 Typical printing system and components of printers:

The following figures are different types of printing machine

1.5.1 (a) contour crafting,
1.5.2 (b) D shape,
1.5.3 (c) concrete printing,
1.5.4 (d) 4-axis gantry,
1.5.5 (e) 6-axis robotic arms printer,
1.5.6 (f, g) And others



2.0 Literature Review

By studying literature review from various authors some were concluded which are follows:

2.1 Foamed concrete

Y.H. Mugahed Amran and colleagues (2015) In order to provide a helpful tool for engineering practice, machine learning is being used to the concrete mix design. For the study, the author created the best ANN architecture and gave it a huge library of concrete mix formulas. A laboratory destructive test is associated with each concrete mix recipe record. The goal of creating a neural network was to predict the compressive strength of concrete generated by a specific composition of concrete mix materials, or, to put it another way, what ratio of ingredients should be chosen to make concrete with acceptable compressive strength. [1]

Cicione et.al (2020) The rheological properties of the first layer will influence the connection with the second, and adhesion at the interface between these two layers is critical for the structure's tensile strength. The time gap has no influence on the modulus of the subsequent layer, but it does boost the modulus of the first layer. It's hypothesized that the first layer's high modulus prevented adequate contact and mixing at the interface. Voids emerge at the interface as the time gap expands, reducing the bond strength in a logarithmic pattern.[2]

T.T. Le and colleagues (2012) Based on a parametric study, has provided new insight into the fire behaviour of steel, concrete, and composite sections. For various configurations, trends in bending stiffness, axial stiffness, cross-sectional stresses and strains, thermal curvature moments, and resulting thermal axial forces are depicted. The results reveal that the complex interactions between constituent material models and cross-sectional geometries produce extraordinarily nonlinear behaviour. As illustrated in the steel beam case study, thermal curvature forces due to temperature gradients would only increase until material degradation exceeds thermal elongation. In the concrete slab case study, cross-sectional stresses follow irregular patterns over the section height due to a combination of thermal strains, material strength loss, cracking, and applied pressures. A tension zone might emerge between two compression zones. Increased bending stiffness and thermal forces occur from the addition of concrete tensile capacity, or tension stiffening. As a result, even though internal stresses differed, tensile characteristics predicted nearly equal deflections for varied configurations.[3]

Ehsan Hosseini et.al (2019) The rheological properties of the first layer will have an impact on the connection with the second layer, and adhesion at the interface between the two layers are critical for the structure's tensile strength. The time-gap has no influence on the modulus of the subsequent layer, but it does boost the modulus of the first layer. It's hypothesized that the first layer's high modulus prevented adequate contact and mixing at the interface. As the time difference widens, voids appear at the interface, weakening the bond strength in a logarithmic fashion. Meanwhile, the first layer's high modulus is required to support the successive layers and maintain structural stability. More effort is being done to enhance bond strength while maintaining a high modulus, such as increasing the interface's surface contact area.[2]

Seyed Navid Hashem Moniri et al. (2019) For simulating the flow behavior of fresh SCC, a multiple-relaxation-time LBM with a D3Q27 discrete velocity model was developed. Using the modified Herschel–Bulkley fluid model, the rheology of fresh SCC was approximated as a non-Newtonian material. The mass tracking technique, which is a simple and efficient approach that exactly conserves mass, was used to simulate the free surface. To test the proposed model's capacity to represent SCC flow, a numerical simulation of the slump flow of fresh SCC was done initially. Based on an upgraded L-box test, the model was then utilised to mimic the passing ability and filling ability of fresh SCC in tight places. The simulated results are in good agreement with the published literature's experimental data. This demonstrates that the suggested MRT-LBM can be used to simulate fresh SCC flows numerically.[4]

Tao Ding et.al (2019) New cementations material compositions for 3D concrete printing have been developed, with recycled sand replacing natural sand. Compressive, tensile splitting, and flexural tests were used to study the hardened mechanical properties, with the strain behaviour and failure pattern documented using the digital image correlation (DIC) method. The morphology of this cementation material was studied using SEM. The compressive strength of 3D printed Concrete with recycled sand was somewhat lower than that of specimens with natural sand, and there was no discernable pattern in the development of splitting tensile strength and flexural strength with the presence of recycled sand. The anisotropy in the 3D-printed concrete built from recyclable sand was still noticeable. The use of recycled sand had only a little effect on compressive and flexural strength anisotropy, but it had a considerable effect on tensile splitting strength. If the cost of river sand rise, 3D printing with recycled sand can significantly reduce the cost of 3D-printed concrete.[5]

2.2 Materials

F. P. Bos et al. (2011) The compressive strength and elastic modulus of the LWAC Model for prediction based on artificial neural networks (ANN) The ANN model accounts for the complex and nonlinear link between the mechanical properties of binders, NWAs, and LWAs, as well as the mechanical properties of concrete components. The database for the ANN model was created by collecting experimental data on various mix proportions, material parameters, and mechanical properties of LWAC from the literature. Appropriate input parameters and the appropriate ANN architecture in terms of the number of hidden layers and neurons were determined to increase prediction accuracy. To increase the ANN model's reliability, all training and validation procedures were conducted to five-fold cross-validation.. [6]

Avadhoot Bhosale et al. (2017) The 3D printability and inter-layer bond strength of cementations material were examined using microscopic study in connection to the material's early age attributes and process parameters. The following conclusions may be drawn from the information provided: •When compared to a control mix activated with alkali sulphate salt, the buildability of a large volume fly ash combination with a very little amount of nanoclay (0.5 percent) is significantly higher. Higher performance is connected to the thixotropic property of clay particles, which is responsible for improved early mechanical properties such as yield stress and stiffness. [7]

Chundakus Habsya et al. (2016) The constructability and mechanical properties of 3D printed concrete were investigated in this study. 1. The interlayer interval time has an effect on the buildability of 3D-printed concrete. The testing demonstrated that a greater interlayer gap interval of up to 300 seconds improved the green strength and hence the buildability of 3D printed concrete. 2. In 3D Printed Concrete structures, lateral supports may improve the resistance to collapse owing to buckling failure. A broad connection width between the lateral support and the the structural wall boosted the capacity of layer disintegration in 3D printed concrete..[8]

Zeeshan Y. Ahmed et.al (2019) Instead of the analytic right-hand side of the kinetics model for early-age hydration of Portland cement, the flexible neural tree structure is generated with observed data. The gene expression programming algorithm and particle swarm optimization approach was utilised to identify the flexible neural tree topology and its corresponding optimal parameters. In addition, to accelerate the evolutionary process, a graphics processing unit (GPU)is employed. The neural tree kinetics model was created by mining a large amount of time series data on degree of hydration. Experimental[9]

F. P. Bos et al. (2011) The purpose of this research was to test if Acti-Gel and polyacrylamide, two VMAs, might be utilised to print concrete. This necessitated the use of cement, silica fume, fine aggregate, superplasticizer, PVA fibres, and water to test various mix designs. Mixed designs with a binder-to-sand ratio of roughly 1:2 resulted from the studies. Based on study on pumpability, extrudability, buildability, viscosity, compressive strength, and microscopic structure, PAM was determined to be the ideal VMA for printed concrete. PAM generates greater initial yield stress than Acti-Gel, leading in good form stability, as shown in the printed filaments. PAM enhances concrete's cohesiveness, allowing it to produce a smooth, continuous layer with excellent surface quality.Despite the high initial yield stress and cohesiveness, PAM generates shear-thinning, allowing for easy pumping. This feature enables PAM mix designs to meet all three rheological requirements of printable concrete (pumpability, extrudability, and buildability) during the phases of the printing process that are needed.[10]

	Motar	Motar with Epoxy	Motar with Epoxy and PVA
Cement	320	320	320
Sand	480	480	480
Water	95	95	95
Super plasticizer	1.5	1.5	1.5
Combond	0	50	50
PVA Fiber	0	0	1.4

2.3 Testing

R Karolina et al. (2017) when the high degrees of uncertainty inherent in structural fire design are taken into account, the findings of predicted and experimental deflections are usually correct. It has been demonstrated that the proposed formulation is appropriate for both concrete and composite constructions. The FBE model predicted the Test 16 runaway failure as well. As a result, it's clear that the suggested FBE model might be useful for predicting collapse loads or fire rating times. It would be important to integrate algorithms in analytical tools for identifying buckling and instability effects, as they would typically not be discovered by the FBE formulation in isolation, in order to make failure more easily predicted. [11]

Sajan K. Jose et al. (2020) The impact of various process parameters on the mechanical performance of 3D printed concrete has been mapped out in an extensive experimental research. The binding strength between the layers is particularly interesting since it appears to be important for structural analysis of printed products. The findings of this investigation show that the manufacturing method has a significant influence on the strength between layers. Only a little effect of layer orientation was discovered in this investigation for the particular process-material combination if the interlayer gap period was kept short enough. The binding strength between the layers, on the other hand, decreases as the interlayer interval duration increases. [12]

Ashfaque Ahmed Jhatial et al. (2020) CMOD experiments on cast and printed concrete at various sizes were used to investigate the influence of inserting short straight steel fibres on the failure behavior of weber 3D 115-1 print mortar. The experiments were also numerically modelled. The fibres create a significant improvement in flexural strength and remove the strength differential between cast and printed concrete without fibres, according to the research. Nonetheless, the post-peak behavior must be described as considerably strain-softening. A robust fibre orientation in the filament direction is seen in the printed specimens. [13]

Fayas C. Subair et al. (2012) In RFC, a coupled LBM-DEM methodology for simulating SCC flows is used, which includes the immersed moving boundary method for fluid-particle interaction. MRT-LBM is used to characterise the fluid, whereas DEM is used to solve the movement of the particles. Particle sedimentation in Newtonian and Bingham fluids is used to validate the suggested approach. The suggested coupled LBM-DEM technique is capable of replicating SCM flow in RFC while taking particle collision in SCC into account. The proposed method was accurate when compared to the literature. More crucially, it can account for the nonlinear instability of particle flow caused by particle collisions in SSC. [14]

Sharipudin, S.S. et al. (2012) Construction applications are increasingly utilizing 3DP technology. This paper analyses different extrusion printing end-effectors for 3D printed mortar and concrete shapes using a 6DOF industrial robot. The utilisation of various mix designs to maximise cementations mix designs with various delivery systems was investigated. In addition, the many trials and tests that were used to evaluate these combinations were detailed. Furthermore, it was discovered that optimizing the cementations mix had a substantial impact on the robot's structure. The printed specimens were subjected to the testing programed in both their fresh and hardened states. [15]

Manjit Kaur et al. (2016) A system that could entrain these cables during printing was disclosed, resulting in a single automated production process. The researchers conducted a pull-out test on cast and printed concrete with varying embedment lengths and three types of reinforcing cables, as well as a four-point bending test on printed beams using the same three cables. In a pull-out test, the binding strength of cables in cast concrete was found to be lower than conventional ribbed rebar but somewhat higher than smooth rebar. [16][17]

3 Techniques for enhancing the performance of layered concrete 3D printing:

Interlayer bonding is one of the seven problems of present 3D printing technology for concrete that has been summarized and is actively being researched by researchers. This section introduces four ways for dealing with the problem. Epoxy and PVA fibers help with adhesion. Strengthen the interlayer bonding strength GO is utilized to lower ASR, which results in 3D printed concrete layers have severe dimensional fluctuations and fissures. TMDs are being researched for a variety of reasons.3D printed concrete has the potential to be used for sensing purposes.

3.1 Epoxy
3.2 Polyvinyl alcohol (PVA) fibre
3.3 Graphene oxide (GO)

4 Experimental test for 3D Printed Concrete

4.1 Trial Mixture
4.2 Slump test
4.3 Print Quality
4.4 Shape Stability
4.5 Printability Window
4.6 Compressive test

5. Conclusion

Following are the conclusions from the review study:

With advancements in the sector of construction, a variety of approaches for introducing automation to the business have been proposed. 3D printing is one of these methods, and it is gaining traction faster than the others. The issue with 3D printed mortar stems from within. The area where the layers of extruded mortar interact is known as the interaction region. This area displays. Due to a lack of strength, a moderate shear force can readily separate the layers. An experimental programme, SEM characterization, and MD modelling were used to assess two enhancement options that were offered. One solution was to use a thin coating of epoxy adhesive between the layers of mortar. The second strategy is to PVA fibers were incorporated into the epoxy-mortar system. In addition to the epoxy adhesive, MD modelling was also used to analyse a carbon and sulphur polymer.

The following is a list of resources conclusions have been reached.

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