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Rethinking indigenous and ecological building materials through the means of additive manufacturing.

Repensar los materiales de construcción autóctonos y ecológicos a través de los medios de fabricación aditiva.

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ABSTRACT

Additive manufacturing or 3D printing can be a feasible strategy that can significantly reduce the time and manual labor required and translate into skilled labor and reduce the wastage of material required during construction. The process in all would also be cost-effective (van Woensel et al. 2018). The challenge posed is the proper implementation of additive manufacturing for full-scale clay-based building materials. Clay-based architecture or mud architecture has been prevalent in India for centuries. Mud construction techniques have been utilized in various climatic zones based on the context and cultures. The versatility of the material allows it to be used as small modules like mud bricks and tiles to grandiose rammed earth walls. It is a highly adaptable material that can change its function as per the strategies used. Another important aspect is the skilled labor that is required to achieve clay architecture techniques (Salas, L. 2022). The rise of cement construction has affected skilled labor, forcing people to migrate to the cement construction sector. The essence and knowledge of these vernacular construction strategies are thus slowly disappearing. This study will be a significant part of realizing the usage of local material to develop future habitable spaces. The help of innovative material systems and 3D printing will help incorporate traditional materials and translate them into solving dwelling problems.

Keywords: Additive Manufacturing; local material; rapid construction; sustainable solution; scalability; robotic 3D-printing.

RESUMEN

La fabricación aditiva o la impresión 3D pueden ser una estrategia factible que puede reducir significativamente el tiempo y el trabajo manual requerido y traducirse en mano de obra calificada y reducir el desperdicio de material requerido durante la construcción. El proceso en general también sería rentable (van Woensel et al. 2018). El desafío que se plantea es la correcta implementación de la fabricación aditiva para materiales de construcción a escala real a base de arcilla. La arquitectura basada en arcilla o arquitectura de barro ha prevalecido en la India durante siglos. Las técnicas de construcción con barro se han utilizado en varias zonas climáticas según el contexto y las culturas. La versatilidad del material permite que se utilice desde pequeños módulos como ladrillos de barro y tejas hasta grandiosos muros de tierra apisonada. Es un material altamente adaptable que puede cambiar su función según las estrategias utilizadas. Otro aspecto importante es la mano de obra calificada que se requiere para lograr técnicas de arquitectura en barro (Salas, L. 2022). El auge de la construcción con cemento ha afectado la mano de obra calificada, obligando a las personas a migrar al sector de la construcción con cemento. La esencia y el conocimiento de estas estrategias constructivas vernáculas van desapareciendo lentamente. Este estudio será una parte importante de la realización del uso de material local para desarrollar futuros espacios habitables. La ayuda de sistemas de materiales innovadores y la impresión 3D ayudarán a incorporar materiales tradicionales y traducirlos en la solución de problemas de vivienda.

Palabras llave: Fabricación Aditiva; material local; construcción rápida; solución sostenible; escalabilidad; Impresión 3D robótica

INTRODUCTION

The construction industry has a great impact on the global economy and due to current inefficiencies is decreasing the ecological footprint (Barbosa, F. et al. 2017). The ease of construction by the means of cement has leaned the whole industry towards it without realizing the high impact factor on the environment. The building industry in expeditiously developing countries needs to find innovative approaches to meet the increasing demand for rapid construction. Thus, it is the need of the hour to switch to alternate solutions of cleaner sustainable materials. Clay with that respect has always been an ecologically sound material and with new innovative techniques has proved its durability again. Compared to conventional methods of construction, robotic fabrication allows designers to create complex forms with higher functionality, efficiency, and customization in less time. This system significantly reduces the energy required for manual labor and the wastage of materials during the general construction period. This proposal aims to develop a set of rules to be followed while considering local material for 3D printing, reducing the long–term costs whilst decreasing carbon footprints. This research will focus on understanding the strategies required for locally sourced and contextually appropriate material using robotic 3D printing and incorporating computational design to find an economically sound solution that can be universally applicable and adaptable.

LITERATURE REVIEW

VERNACULAR ARCHITECTURE

Earth construction has been historically documented as early as 3300 years ago. In the city of Thebes – the Ramasseum built around 1300 BC was made of adobe bricks. Tabo monastery, Spiti valley in India is the oldest earthen building which has withstood the harsh winters of the Himalayas since 996 AD. (Auroville Earth Institute, n.d.) It is only after the industrialization age that the construction industry shifted its alignment to cement and concrete construction to such a huge extent. But with the emphasis on sustainability, earth construction is making a comeback. With the latest construction techniques, earth construction can be mobilized to be faster, better, and more effective.

ADDITIVE MANUFACTURING (AM) - LARGE SCALE 3D PRINTING

The manufacturing industry accounts for a massive energy consumption globally. The introduction of AM allows for reducing this consumption smartly and efficiently. One segment of AM is 3D printing. The advantage of on-site large-scale 3D printing is that it digitizes and streamlines all significant stages of construction, from project planning to execution (Mechtcherine et al., 2019). It can help with increasing the skilled labor workforce which is a current issue for the development industry. There are various innovative modes of large-scale printing such as Cartesian robots – Contour crafting (CC), SCARA – Selective Compliance Assembly Robot Arm, Delta robots – Big Delta 12M WASP. This method allows on-site printing by reducing material wastage which decreases cost and carbon footprint. It also enables the reuse of waste material and decreases the time of construction due to the material output precision through the calculative digital code. Figure 1 below depicts the procedure of 3D printing.

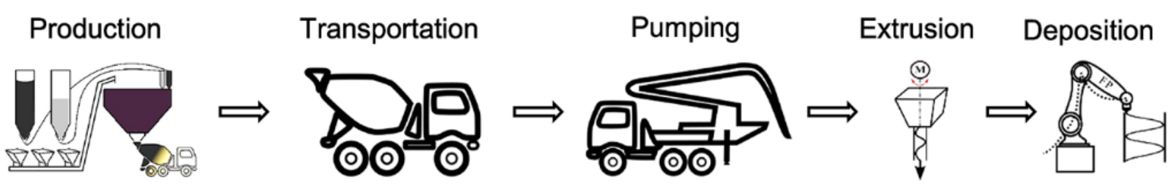

Fig 1: Production outline for 3D printing (Nerella, 2015)

LARGE SCALE 3D PRINTING IN INDIA

In the Indian context, large-scale on-site 3D printing has also accelerated. The collaboration of IIT Madras startup Tvasta helped develop India's first 3D printed house using concrete as part of their base mixtures. The house was printed in 21 days, reducing construction costs by 30% (Manoj, A. R, 2022). Parallelly, explorations to build with mud are also being explored in various parts of the country, the prime focus being at the MinVayu fab lab at Auroville (MinVayu Open Source Development Project, 2021). They are developing an open-source large-scale 3D printer that produces customizable mud bricks.

BUILDING MATERIAL

The building material essentially used for large-scale 3D printing is concrete-based mixtures. The material extrudability for printing varies on the type of machine utilized. But concrete production for these machines adds to already increasing ecological and sustainability concerns that the material possesses. Thus, alternate

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environment-friendly materials are being explored with clay being at the forefront for its ease of accessibility in and around sites of construction. The usage of the local material also reduces the carbon footprint associated with it. The following timeline (Figure 2) depicts the amount of research conducted with various building materials in terms of 3D printing.

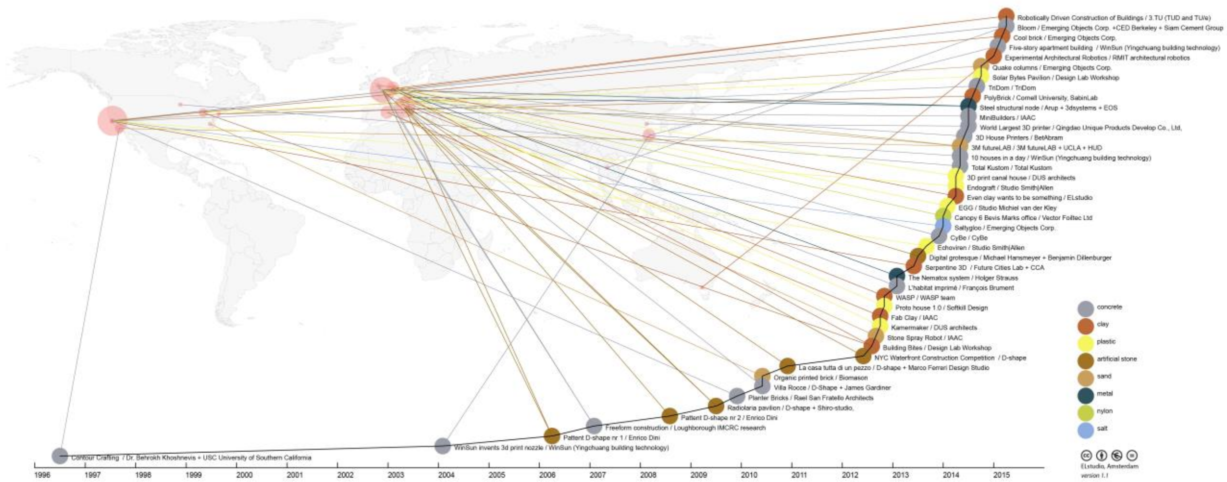

Fig 2: Timeline of materials used by various research groups (Langenberg. E, 2015)

STATE OF THE ART

The 3D printing applicability can be seen through a few current scenarios. Gaia House, 320 sqft in the plan was constructed within ten days (Chiusoli, 2018). It is a project by WASP, a 3D printing studio in Massa Lombarda, Italy. The materials used were earth (25%), rice straw (40%), rice husk (25%), and hydraulic lime(10%). The geometry of the wall through computational design optimized the utilization of the material mix leading to an efficient building construction technique. The printer used here is the Crane WASP, which suspends the main printing head through a crane-shaped frame. In Mexico, with the help of the non-profit organization, New Story has begun to build the first phase of 3D printed houses in Tobasco, Mexico (Grace, 2019). With a conscious consideration of the feedback from the local dwellers, they were successful to build housing units of 500 sqft each in collaboration with ICON, the construction company helping out with Vulcan II, which is based on contour crafting method of printing. Each house took only 24 hours to build. The material utilized here is a modified form of concrete, patented by them and termed lavacrete.

MATERIAL AND METHODS

This research has a mixed methodology approach which includes literature review, strategies for elementary steps for on-site large-scale 3D printing, and researchers' insight and understanding. The study began with understanding the basic composition of clay and the observations made when natural additives sourced from the immediate surroundings were integrated. The objective was to create a basic collection of parameters that could be adhered while executing strategies in multiple contexts. The flow chart (Figure 3) below sheds light on the process.

Fig 3: Flow of research process

MATERIAL PROPERTIES

The building materials utilized for this research were sourced from around the city. The various materials other than the base of clay were termed natural additives which could be broadly categorized into enzymes, collagens, and starch. The enzymes were extracted from sugar cane while collagens include the by-product of fisheries. The starch category included residue from wheat, rice, and corn. The additives were added in certain proportions to the clay to understand the physical properties of the composite material thus obtained. The two experiments conducted were (a) block test to understand the binding of this composite material and (b)extrusion test to understand the viscosity of the composite materials.

GEOMETRIC TOOLKIT

In the type of 3D printing strategy considered, the material extrudes and deposits layer by layer. Thus, it is important to understand the reaction of the composite material in both wet and dry states while printing the structure. Taking this into consideration, a parallel study was conducted to understand the basic structural parameters namely: bending moments, inertia, the center of gravity, and overhang angle. A catalog of basic geometries was 3D printed using clay to deduce initial observations. As depicted in Figure 4, during the wet stage of printing, the behavior of the printing modules was observed. Buckling was observed in most cases due to lack of support on the wall and load of the material deposition in the subsequent layers. Also, in a few cases, the design at the footing covered a low surface area leading to unstable structures (Datta et al., 2019).

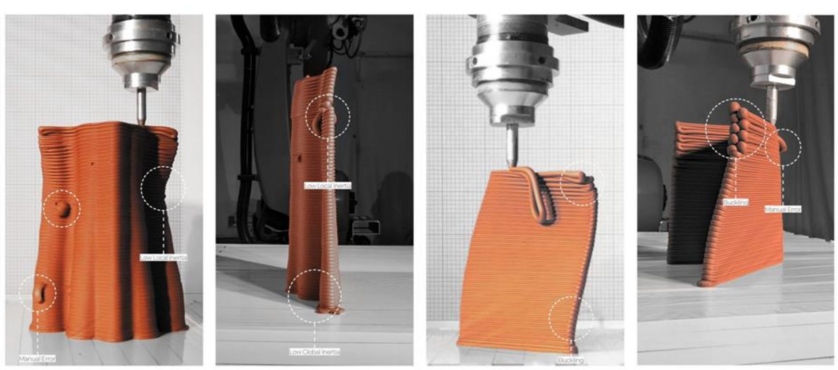

Fig 4: Test prints to analyze structural parameters (Datta et al., 2019)

PRINTING STRATEGY

The study conducted in section 3.2 helped realize the need for infill design to help the geometries attain structural stability and optimize the quantity of material. The infill design also helps in the continuous print of the geometries. Thus to create a wall with this strategy, it would require a geometric strategy where the external surface and infill design are incorporated. The pattern created would also allow the circulation of air which helps in drying the printed material. The figure below depicts a study of infill design in different types of printing paths (Fig 5).

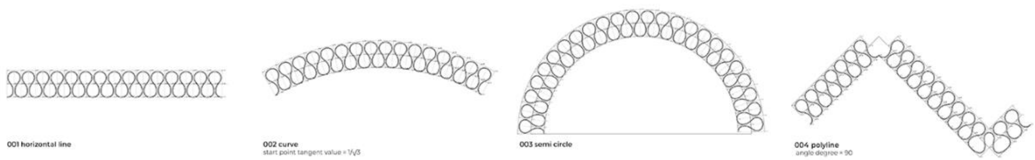

Fig 5: Infill Design (Datta et al., 2019)

RESULTS & DISCUSSION

The above-stated method in section 3 led us to create a set of rules that can be followed at the beginning of any design strategy. Figure 6 depicts the major factors to be considered while designing a geometry. The external and internal equilibrium essentially deal with the center of gravity(CG) of the structure during the wet and dry stages of printing. Figure 6(a) informs how the CG of the geometry will keep on shifting after each layer is extruded. This occurs during the wet stage of printing. Thus there will be an overall shift in CG when the last layer is printed. Figure 6(b) explains the global CG in the dry state of the geometry. If the CG falls outside the support area, then there is a chance of failure in the structural stability of the geometry. Figure 6(c) specifies that to increase structural stability during the wet stage the geometries should have many small kinks to hold them in place. This explains the importance of the infill pattern that helps in stabilizing the prints as mentioned in section 3.3. Figure 6(d) depicts the analysis conducted of the geometry's overhang load and if it can be internally balanced by the overall structure.

Figure 7 illustrates the summary of the experiments carried out in alignment with the material properties mentioned in section 3.1. Figure 7(a) describes the atomic composition of clay. Brick dust and marble dust are added along with form the base mixture to which the various natural additives are added to be tested for different parameters. The chosen additives are further tested using the manual extrusion method in Figure 7(b) to understand the plasticity of the various compositions. To achieve a smoother extrusion and an optimized drying time, dry ash from dead leaves residue is added and the extrusion test is conducted again. Parallelly, the selected

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compositions have undergone a compressive strength test as shown in Figure 7(d). Lastly as depicted in Figure 7(c), an automatic extrusion test has been done to observe the adhesion and resolution of the geometry printed.

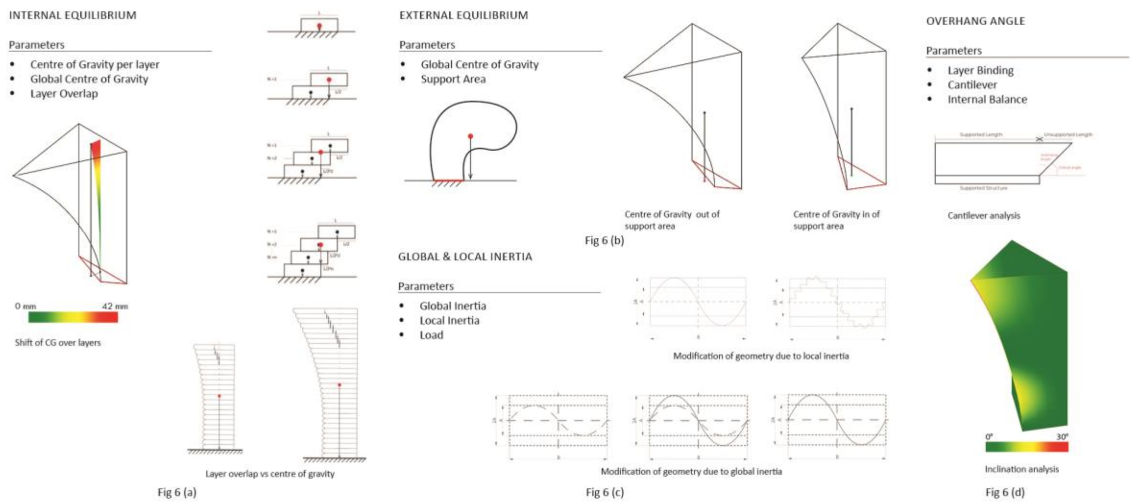

Fig 6: Structural Analysis Toolkit (Datta et al., 2019)

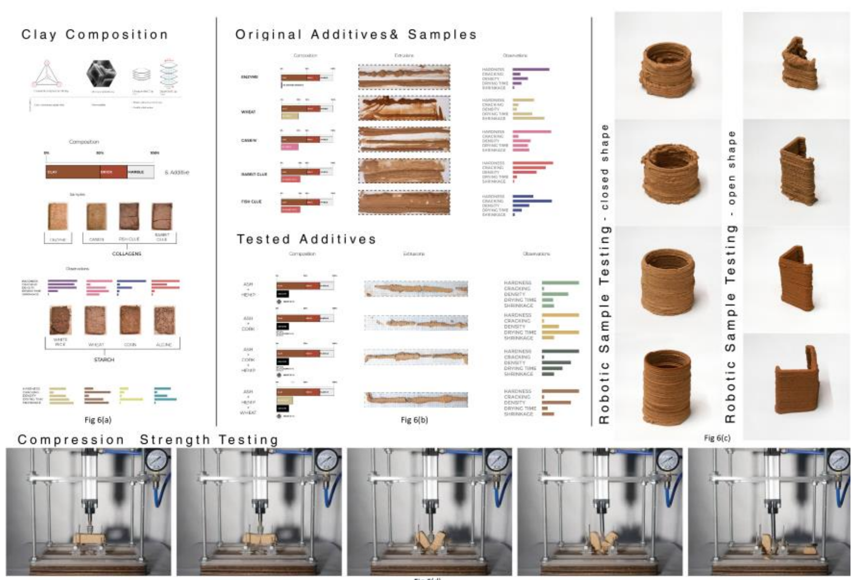

Fig 7: Material Toolkit Analysis (Datta et al., 2019)

The research is based on a case study and literature review. As the study is highly dependent on the local materials available, specific materials accessible in a similar context might be a limitation. This paper proposes a new model of understanding the factors involved in utilizing a composite material derived from local materials available close to sites of construction. It also identifies the several structural considerations to be reviewed before beginning on-site printing. This research principally aims to understand the method of additive manufacturing and analyze indigenous materials to help reduce carbon footprint and help in sustainability. Even though, the methodology and the results are based on situations focused on local context, the parameters and factors proposed can be used as generic standard for analysing similar experiments conducted in other contexts.

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