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Assessing Concrete Performance in 3D Printing: A Comparative Study of M-Sand and River Sand

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Abstract: This paper's primary goal is to make an initial attempt to learn about and comprehend the various facets of concrete 3D printing. We have studied materials, printing parameters, finished and ongoing projects, and we have tested 3D printable concrete with materials that are readily available in our locality. This work examines a variety of historical data on mix design proportions, draws a general conclusion about the effects of mixture compositions on characteristics, particularly on the fresh and hardened stages of 3DPC, highlights those effects, and describes mix design methodologies. Right now, we continue to use a trial-and-error methodology, which is standard practice. In order to accomplish design goals that are common to particular 3D printer parameters and that should be widely accepted, we need to develop a set of standard guidelines.Here, the idea of manual extrusion—manually printing 3D objects with a hand-held extruder—is presented for experimental purposes.
Keywords: Concrete, materials, readily, historical data, proportions, trial and error, extrusion, 3DPrinting

I. INTRODUCTION

3D concrete printing is a new age and an innovative construction technique that is progressively making its way into building construction sector to provide a secure, customized, aesthetics and duration of construction.As 3D printing became more widespread, the building sector adopted the technology to create homes and other construction projects. The benefits of on-site assembly, lower time and cost and improved quality are driving the daily growth of concrete 3D printing. The concrete specifically utilized for 3D printing, however retains the consistency feel of an aerated dough which having elements identical to traditional concrete. Such 3D printed structures are globally constructed.There are no standards for construction of 3D printing and therefore there is list of researches being carried out. The material efficiency of additive manufacturing procedure is greater compared to traditional construction process [Joseph Pegna (1997)]. The use of cementitious materials in 3D printing is an emphasis on reasonable and sustainable choices. There are six possible replacement ratios of tailing to sand for a single nozzle printing technique. The ideal mixture contains about 30% mining tailings [Guowei Ma et al (2017)]. This technique reduces the industrial waste; reduce housing gaps and labour and energy costs [N.I. Vatin et al (2017)]. It is a cutting-edge technique that creates complicated shapes from 3D CAD designs without need for tools [Yi Wei Daniel Tay et al (May 2017)]. The latest advancements in 3D printing technology emphasize contour crafting as a revolutionary approach for building environmentally friendly dwellings. 3D printing and traditional construction methods will likely continue to evolve alongside each other in the future [Mehmet Sakin and Yusuf Caner Kiroglu (July 2017)]. In the industrial sector, 3D printing offers possibilities for automation, production acceleration. However, its potential in the building sector is restricted due to scarcity of materials and expensive processes [Isaac Perkins & Martin Skitmore (2017)]. The total amount of energy required for building construction, replacement, restoration, and demolition accounts for 48% of the world's yearly energy consumption. With 3D printing technology, energy usage and carbon emissions can be decreased [M K Dixit (2019)]. The combined effect of Industry 4.0 technology with 3D printing presents significant opportunities for more productive and sustainable construction. But the building industry has not completely embraced 3D printing technology, and incorporating robotic systems into large-scale construction projects is the main obstacle [S. El-Sayegh et al (March 2020)]. The demand for labor may be reduced by this technology, especially in nations with large immigration rates. This might not be helpful, in nations where building is the main sector and labor is less expensive. Additionally, 3D printing requires specialized knowledge and may require high-level positions [Md. Aslam Hossain et al (Oct. 2020)]. 3D printing could become a viable alternative to conventional methods, transforming industry management in remote, isolated, and expeditionary environments [S.J. Schuldt et al (March 2021)]. This technology requires 3D model design, optimized cement mortar, and careful mixing ratios.

It offers financial and ecological benefits, but its application depends on precision, material, cost, and duration [Asena KARSLIOĞLU (March 2022)]. New design methodology that integrates fabrication and assembly of a flat print bed and a 3-axis gantry robot-equipped concrete extrusion 3D printer to create an overhanging, compression-dominated structure made of interlocking, modular 2.5D concrete segments. This formwork-free concrete 3D printing method allows for faster and easier customization of the geometry of overhanging concrete structures based on different site and structural design requirements [Alexander Lin et al (2022)]. 3D printing is the most flexible building technique, promoting creativity, error reduction, and a shorter supply chain. However, the lack of regulations and rules governing 3D printing production and usage raises concerns about public safety and the environment. The study suggests that appropriate laws and policies should be implemented alongside 3D printing to protect people and reduce environmental damage [Waqar et al. (Feb. 2023)].

II. LITERATURE REVIEW

Joseph Pegna (1997) investigated a new additive manufacturing technique for construction automation, which simplified assembly operations. He investigated masonry constructions constructed by applying Portland cement and sand, revealing distinct mortar properties. Pegna also evaluated the potential for large-scale, solid freeform structure production.

Zeina Malaeb et al. (2015) stated that 3D concrete printing as a viable construction method. This method permits formwork-free construction of homes with the appropriate mix that meets architectural criteria. The printer works in three dimensions to efficiently construct walls and other structures. It optimizes the extrusion process by using a nozzle and trowels with a diameter of 2 cm. Experimentation revealed the appropriate mix: 125g cement, 80g sand, and 160g fine aggregates, plus performance additives, resulting in a compressive strength of 42 MPa.

C. Gosselin et al (2016) developed a new 3D printing method for ultra-high-performance concrete, combining various disciplines. Their innovation allows for large-scale, sophisticated structures to be built without the use of temporary supports, hence enhancing 3D printing in architecture. In addition, the technique allows structural components to be multifunctional.

Pshtiwan Shakor et al (2017) developed a cement mixture for Z-Corporation's 3D printing, hoping to replicate Z-powder. They assessed the mechanical properties using cubic specimens with varying saturation levels. The study proposes Z-Corp 150 as an alternative for Z-powder in 3D printing, enhancing compressive strength.

Guowei Ma et al (2017) investigated the use of cementitious materials in 3D printing with an emphasis on affordable and eco-friendly options. It develops a single-nozzle printing method and looks at six replacement ratios of tailing to sand. Thirty percent mining tailings is the ideal blend.

Hambach and Volkmer (2017) discussed 3D printing with fiber-reinforced Portland cement, a material recognized for its high flexural and compressive strength. They used aligned glass, basalt, or carbon fibers to increase strength, carefully controlling their alignment along the print path.

N.I. Vatin et al (2017) conducted a global assessment of additive technology in construction, focusing on its potential for waste reduction and cost efficiency. They studied fundamental printing technologies and market players with the goal of promoting innovative construction techniques in Russia. Key obstacles cited include a lack of regulations, industry expansion, and expensive equipment costs.

Yi Wei Daniel Tay et al (May 2017) investigated 3D printing, which is a toolless approach for sculpting complicated objects from computer models. It speeds up prototype manufacturing, reduces material waste, and revolutionizes building techniques, lowering prices and labor. The Singapore Centre for 3D Printing displays current advances, highlighting possible future research directions.

Mehmet Sakin and Yusuf Caner Kiroglu (July 2017) discussed 3D printing improvements, including contour crafting for sustainable housing. They highlight the reduced costs, reduced pollution, and safety benefits. The integration of BIM and 3D printing promises greater efficiency and design. BIM synchronizes 3D printing systems, defining future plans and generating revenue. The study forecasts that 3D printing will continue to evolve alongside traditional construction methods.

Ali Kazemian et al (2017) developed the workability of a new "printing mixture" for construction-scale 3D printing. It focuses on print quality, shape stability, and printability window, using measurements of printed layer size and surface quality. The study suggests an iterative laboratory testing approach that emphasizes printed layer characteristics rather than pump usage, allowing for compatibility with various concrete 3D printing systems.

Isaac Perkins&Martin Skitmore (2017) investigated 3D printing's potential in manufacturing for automation and waste reduction, but found limitations in construction owing to material constraints and pricing. Techniques like as contour crafting and concrete printing encounter scalability and practicality issues on large projects.

Refilwe Lediga&Deon Kruger (2017) investigated flexural strength and discovered a range of 13 to 16 MPa, with tension between layers resulting in a 36% drop in loading. Bonding between layers is critical in 3D concrete printing, with timing impacting adhesive strength and shrinkage being a concern. Optimizing mix design and nozzle diameter can improve buildability and compressive strength while meeting building codes over time.

Nils O.E. Olsson and Ali Shafqat (2019) highlighted the limited use of 3D printing in Norwegian construction, primarily for testing. Long-term, it is cost-effective, but it requires over 8 years of implementation and significant investment. Encouraging R&D support and collaboration among suppliers and contractors may aid in widespread adoption. 3D printing holds potential for non-standard building components, but more technological improvement is required.

M K Dixit (2019) discovered that buildings utilize 48% of global energy annually, with significant embodied energy in construction. 3D printing has the potential to reduce energy use and emissions, but it faces challenges in traditional construction processes. Future research should prioritize iterative design and implementation in order to fully capitalize on its benefits.

S. El-Sayegh et al (March 2020) studied 3D printing in construction, highlighting advantages such as constructability and sustainability, as well as dangers such as material printability and lack of regulation. They filled a literature void by addressing risk, which is a novel feature of 3D printing. While promising for sustainable building, full integration into construction faces obstacles, particularly with large-scale projects and robotic systems.

Md. Aslam Hossain et al (Oct. 2020) noticed the construction industry's shift toward automation, particularly 3D printing, to reduce labour costs. Its suitability is dependent on labour costs and a country's reliance on construction. However, knowledge and investment barriers may outweigh cost benefits in materials, labour, and time.

Lotfi Romdhane and Sameh M. El-Sayegh (Nov. 2020) examined 3D printing in construction, citing benefits such as speed, cost reduction, and design flexibility, as well as issues with materials and regulations. Despite the challenges, 3D printing has promise for the future of construction.

S.J. Schuldt et al (March 2021) reviewed 4491 papers on 3D-printed construction published between 1998 and 2019, indicating that it has the potential to replace traditional methods in remote regions. They highlighted seven essential factors, including materials and cost, and emphasized the necessity of technical advancements and case studies. The report emphasizes 3D printing's potential to alter industry management in remote regions with continuous investment.

Ning et al. (April 2021) used quantitative and qualitative research to investigate the current state, difficulties, and future directions of 3D printing (3DP). They investigate both technical and non-technical aspects, such as materials, processes, and societal implications. Their findings provide a theoretical underpinning for existing practices and future uses in building. However, constraints due to a lack of scientific publications may have an impact on the study's results.

Zhang D. et al (May 2021) demonstrated 3D printing's disruptive potential in construction, but its widespread adoption is impeded by material and technical obstacles. Despite its adaptability, current technology falls short of addressing industry requirements. Innovation efforts are underway, but the overall impact is questionable. Regulatory backing is critical for widespread 3D printing use in building.

Asena KARSLIOĞLU (March 2022) investigated that advancements in technology are transforming the building industry, with 3D printing becoming increasingly popular for creating small-scale products and intricate structures. This technology requires 3D model design, optimized cement mortar, and careful mixing ratios. It offers financial and ecological benefits, but its application depends on precision, material, cost, and duration. Directed energy deposition and powder bed fusion are the best methods.

Alexander Lin et al (2022) invented a revolutionary design approach to create overhanging structures out of interconnecting concrete pieces using a flat print bed and a 3-axis gantry robot-equipped concrete extrusion 3D printer. Tested in a lab setting, this approach allows for quick customization without the need for formwork. In the future, piece-by-piece assembly ought to be the main focus to expedite construction.

A. Jandyal et al. (2022) has investigated that while 3D printing has advanced significantly, there are still problems that need to be addressed including material incompatibility and material expense. More attention needs to be paid to creating affordable printer technologies and materials that work with these printers in order to increase the number of applications for 3D printed items.

Y. Zhao (2022) looked at the negative effects of conventional building techniques on the environment and resource inefficiencies. Expanding upon these observations, 3D printing technology offers enormous possibilities for personalized constructions and tackles conventional construction obstacles. This study evaluates concrete 3D printing's developments in materials, equipment, defect management, and application contexts, providing suggestions for future growth. Concrete 3D printing emerges as a critical emphasis.

Waqar et al. (Feb. 2023) examined the effects of 3D printing on residential projects in Malaysia, stressing the necessity for restrictions while also noting the benefits to safety and the environment. Although there are hazards associated with regulatory limitations, integrating 3D printing into home construction offers innovation and efficiency. The report emphasizes how crucial it is to have legislation in place in tandem with improvements in 3D printing to guarantee public safety and environmental protection.

III. 3D PRINTABLE MATERIAL PROPERTIES

Cement-based 3D printing materials have the same composition as traditional materials. The nozzle's size limits the options available for choosing aggregates. You cannot utilize coarse aggregate larger than 2.36mm because of the limited nozzle dimension. The concrete in its fresh state goes through different stages such as selection of materials, mixing, pumping and deposition in a layer by layer.

A. Cementitious Materials

Because it is widely available and reasonably priced, Portland cement is the most widely used material in building; both for traditional concrete applications and 3D printed ones. Supplementary cementitious materials are used in place of certain Portland cement in order to lower CO_2 emissions and minimize production costs while keeping an eye on the environment and the economics. A number of components that were formerly considered waste from manufacturing processes, such as fly ash, slag, and silica fume, are now recycled and used as binding agents in cement mixtures. The qualities of these additional cementitious elements influence printable concrete's pumpability, extrudability, and buildability.

B. Aggregates

Aggregates, one of the most crucial parts of 3D printed concrete, significantly affect as well as influence the quality of concrete (Rahul et al., 2020). River sand is becoming more and more scarce, thus manufactured sand has been utilized to fill its place. Concrete's workability, mechanical qualities, and durability have all been shown to be significantly impacted by aggregates, both experimentally and theoretically (Yaxin et al., 2022).

C. Fly Ash

One of the primary by-products of producing electricity from coal power plants, fly ash, is another substance that is utilized in place of Portland cement. Because it is more environmentally friendly to use recycled fly ash—which has already been created—instead of producing additional OPC and releasing needless CO_2 into the atmosphere, this material is used in place of Portland cement.

D. Water-Binder Ratio

For printing, high performance concrete mixes with water to binder ratios of 0.21 to 0.41 are recommended. To complete the hydration process and get the best long-term durability and mechanical performance, low-w/b blends need more curing water (Gerrit et. al 2021).

E. Admixtures

To create printable concrete, a complex mix design containing exact additive proportions is required due to the conflicting rheological specifications for concrete printing. Any substance that is added to a cement mix—apart from water, cement, aggregate, and fibers—before or during the mixing process is referred to as an admixture. Admixtures can be used for a wide range of purposes, including minimizing slump, decreasing water content, accelerating or delaying set times, and enhancing workability, strength, and durability. For the purpose of additive manufacturing, a particular blend of admixtures, including retarders, water reducers, and accelerators, is needed.

F. Dynamon Sx 630 (Superplasticizer)

A modified acrylic super plasticizer for concrete, which has a lengthy workability period, a low water-to-cement ratio, and extremely high mechanical strength. Dynamon Sx is ideal for applications that require significant water reduction and excellent mechanical strength at early stages. Dynamon Sx is ideal for producing self-compacting concrete because of its outstanding workability.

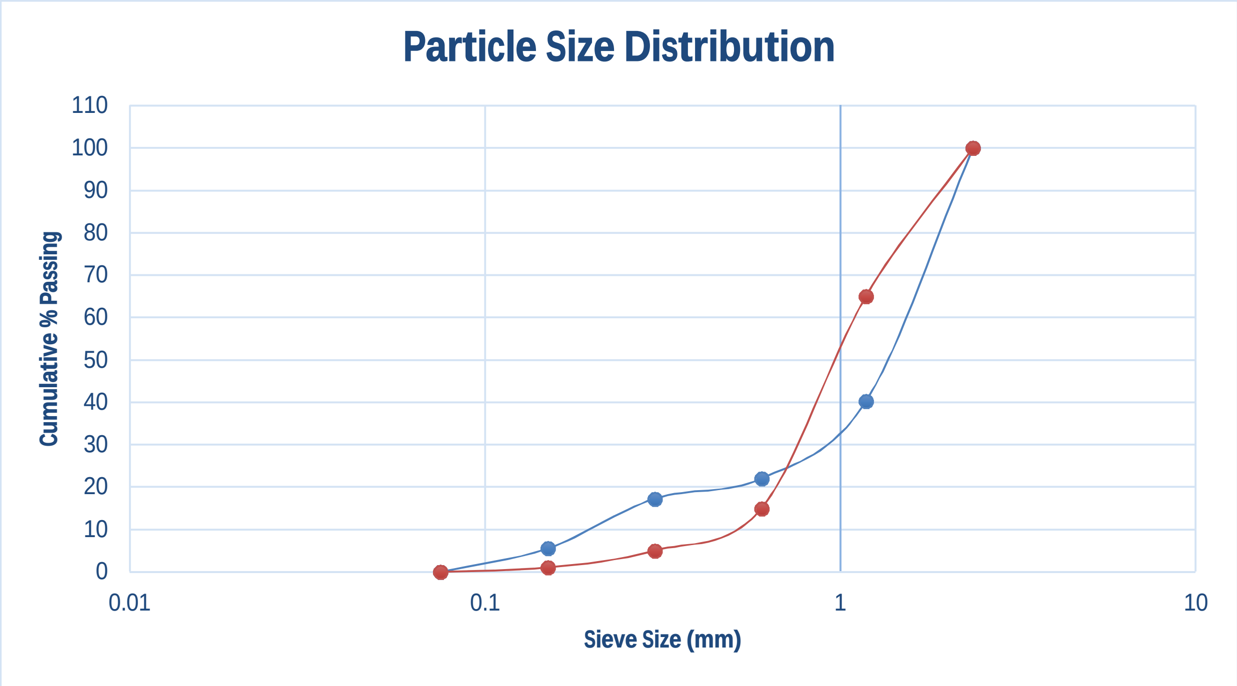

Figure 1: Graph showing the particle size distribution from a sieve analysis done on river sand (●) and m-sand (●).

IV. MIX DESIGN

An extensive series of experiments was required to arrive at the final ideal mix for concrete printing. Hand mixing method was used. Cement, sand, and water were the basic ingredients used in the initial testing combinations. Trial combinations with different additions were then assessed and revised iteratively until a limited number of printing-suitable mixtures were obtained for a particular admixture. The procedure was then repeated with a different admixture to see which blend designs would work best for printing. Four trial mixtures totaling different material quantities and combinations were assessed. The most appropriate combinations were then tested for pumpability, extrudability, and buildability—the three essential characteristics of printable concrete—after extensive experimentation. A typical slump test was used to determine pumpability, a prototype extrusion nozzle was used to determine extrudability.

Table 1: Mix Design for River Sand

Mix Number	Cement (PPC) (Kg)	Sand (kg)	W/c Ratio	Superplasticizer (%)	Result
1	1.21	1.79	0.35	0.35	Fail
2	1.05	1.95	0.35	0.4	Fail
3	1.275	2.22	0.36	0.4	Fail
4	1.275	2.22	0.37	0.45	Pass

Table 2: Mix Design for M-Sand

Mix Number	Cement (PPC) (Kg)	Sand (kg)	W/c Ratio	Superplasticizer (%)	Result
1	1.20	1.80	0.35	0.4	Fail
2	1.095	1.905	0.35	0.45	Fail
3	1.26	1.74	0.3	0.25	Fail
4	1.095	1.905	0.33	0.21	Pass

V. TESTING PROCEDURES

A. *Flowability Test*

One important factor in assessing the printing performance of a concrete mixture is flowability. Ensuring that the paste is easily pumpable in the delivery system and depositable in the deposition system is the goal of flowability control. DYNAMON 630 superplasticizer was utilized to increase cement paste flowability while preserving compressive strength at low water content.

B. *Extrudability Test*

An adequate level of extrudability, or the ability for material to be constantly supplied through tiny pipes and deposited from nozzles at the printing head, is required of the cementitious materials used in 3D printing. The smooth grading of materials is the key to controlling the extrudability of concrete material for 3D printing. Following sieve analysis, the sand was graded into different sizes. Zone 2 and Zone 3 proportions were then achieved by combining the graded sand.

Figure 2: Prototype (GI pipe) used for extrudability testing

C. *Open Time Test*

The amount of time that the material is still workable and flowable for the printing process is referred to as the printing open time in 3D printed concrete. A more accurate way to depict how concrete workability changes over time is using open time measurement.

Figure 3: Open time test done for time interval of 5 min.

D. *Shape Stability Test*

One essential aspect of fresh concrete printing is shape stability, or the concrete's capacity to withstand deformations during layer-by-layer production. Shape stability test is done to assess if the mixture is strong enough to hold the shape without formwork or support.

Figure 4: Checking the shape of printed concrete for deformations if any

E. Buildability Test

Buildability, or the material's capacity to maintain its extruded shape in the face of pressure from higher layers and self-weight, is another crucial factor to consider when assessing the printed performance of concrete materials. Six layers in all were printed for the buildability metric, and after each layer was added to the next, deformation was noted in each layer.

F. Marsh Cone Test

A dependable and simple technique for examining the rheological characteristics of cements and mortars is the marsh cone test. The amount of time that mortar and cement flow through a marsh cone indicates viscosity, which is dependent on the compatibility of cement with superplasticizer. A straightforward method for gathering information regarding the behavior of cement paste is the Marsh cone test. 1L of cement paste was prepared with the water-cement ratio of 0.35 by adding 2Kg of cement to them.The nozzle is held closed as the fluid material is poured into the cone. The nozzle is opened and the fluid is let to flow freely once the cone has been filled with the prescribed amount of fluid. Marsh cone time is the amount of time required for a measured quantity of material to flow out.

Figure 5: Marsh cone test assembly

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G. Slump Cone Test

The standard ASTM C143 slump test was preferred to check the concrete's pumpability. A typical slump cone measuring 200 mm at the bottom, 300 mm overall height, and 100 mm at the top was used for this test. The cone was filled with the prepared concrete mix in about three equal layers and simultaneously tamping each layer 25 times with the rounded end of tamping rod in a uniform manner over the cross section of the mould. After this mould was raised from concrete slowly in vertical direction and slump was measured.

Figure 6: Pumpability was evaluated using an ASTM C143-compliant standard slump cone

H. Compressive Strength Testing

This test evaluates the concrete's resistance to compression. It is among the most crucial tests for determining how strong concrete is. The ability of the structure to support the load rests primarily on its durability. The compressive strength was determined by using 70.6 × 70.6 × 70.6 mm cubes. Demolding was done after 24 hours of casting. And kept in the curing tank. This was then tested for 7 days and 28 days.

(a) (b) (c)

Figure 7: Compression testing for 28 days cured (a) cubes, (b) Printed layers (river sand), (c) Printed layers (M-sand)

VI. RESULTS AND DISCUSSIONS

To arrive at the ideal combination that can be utilized for concrete printing, a long series of tests had to be carried out. The mix that can satisfy all necessary specified standards while having the lowest water-to-cement ratio is called the ideal mix. A number of mixes were evaluated for extrudability using different ratios of water to cement, superplasticizer, and dry constituents (sand, fine aggregates, and cement) in order to arrive at the control mix.

The combination that met all of the necessary characteristics for flowability, extrudability, buildability, and open time with the least quantity of water-cement ratio was found to be the most effective one. The dimension of the prototype nozzle was 3cmx3cm. The mix's ability to flow out of the nozzle continuously served as a visual test for the extrudability requirements. In order to boost strength while preserving the proper flowability, a superplasticizer was added with the purpose of lowering the water-cement ratio.
Four mixes were tested for river sand as well as m-sand as shown in table 1 &2. The results of the compressive strength test showed that samples 1, 2, and 3 of river sand had strengths of 41.68 MPa, 41.80 MPa, and 56.23 MPa, respectively. Samples of m-sand 1, 2, and 3 had strengths of 58.5MPa, 55.29MPa and 51.40MPa respectively. The desired compression strength of 40 MPa was met and exceeded by all of the combinations. The strengths of the printed concrete layers for m-sand were 29.25 MPa and 13.57 MPa for river sand, respectively. The best strength was evidently obtained with the least water-to-cement ratio. The slump-flow test was performed on the concrete mixtures to measure pumpability, the slump for river sand mixture was found to be 112mm and for m-sand was 110.5mm respectively. The buildability and shape stability were also assessed for the same mixtures with six layers.

VII. CONCLUSION

According to the test results, high strength cement mortar is essential for concrete 3D printing and strong quality control of the materials and processes is crucial. The performance of the materials must be assessed in relation to their mechanical properties in order to create high performance 3D printed concrete. In order to meet the necessary specifications, the effect of additive materials such as binder and admixtures is also very important.
Present research and development efforts are concentrated on generating a wide range of 3D printable construction materials, including sustainable and eco-friendly solutions. It will offer more versatility in construction projects and address both structural and environmental concerns.

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