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Optimizing the Rheology of 3D-Printable Concrete: Future Prospects in the Construction Industry

Mai Megahed[1], Mohamed Abou Zeid[2]
[1]American University of Cairo
AUC Avenue, New Cairo, Egypt
mainas@aucegypt.edu; mnagiba@aucegypt.edu
[2]American University of Cairo
AUC Avenue, New Cairo, Egypt

Abstract **-** 3D Concrete Printing (3DCP) is developing as a transformative technology in construction, offering the prospective for higher levels of design freedom, lower human intervention, and automation for the construction industry. However, optimizing the concrete mix for 3DCP still possess a substantial challenge, particularly when the intention persists to align to the sustainability development goals. The current study investigates and compares the structuration rate of various 3DCP concrete mixes, using a laboratory scale shear vane apparatus to measure the thixotropic behavior and yield stress recovery while incorporating selective materials to act as partial cement replacement. The concrete mixes tested include the usage of metakaolin, biochar, and silica fume as partial replacements for cement. These materials were selected for their potential to improve the sustainability of 3DCP without compromising the desired mechanical performance.

Keywords**:** 3D Concrete Printing, Structuration rate, yield stress recovery, thixotropic behavior.

1. Introduction

3D-Printing in Construction would represent the industrial evolution of the new era. The transition from conventional methods to more automated techniques would require different level of skilled labour as well as specific materials and advanced digital technologies. The significance of 3D-Printing in construction is not just related to the sole reason of it being the slowest industry to enter the world of automation when compared to the other manufacturing applications. In truth, involving 3D-Printing in construction gives hopes to eradicate the construction wastes, accident rates on site, and expedite project timeframe which would consequently lead to overall cost reduction.

2. Case Studies Proving The Perspective Uses Of 3d-Printable Concrete

In 2018, the U.S. Army joined forces with construction companies to 3D print concrete barracks and bridges for military bases in relatively remote areas [1]. Utilizing the technique of 3DCP helped them to expedite the construction of the structures without resorting to large workforces or elevated material transport costs. Similarly, in rural areas of Mexico, ICON built schools via the 3D-printed concrete technology, further showing power of its flexibility [2]. Recently, one of the most globally popular technology providers, completed selective projects which further shed the light on the humanitarian perspective of applying 3DCP in construction namely, the first 3D-printed school in Lviv, Ukraine, 2023, which was headed by the humanitarian foundation Team4UA in efforts to re-build Ukraine's war-torn education infrastructure [3]. Another project completed by Siam Cement Group (SCG), was the remarkable medical facility spanning 345 m² over two floors in Thailand, further demonstrating the viability of 3D printing in larger scale, non-residential type of buildings [4]. The project reduced labor and construction time while integrating sustainability, using advanced 3D printing mortar which was proven helpful in reducing CO_2 emissions. Moreover, the first 3D-Printed large water tanks completed by Abyan company in Kuwait in 2024. The project highlighted the versatility offered by 3DCP in customizing the design and materials used to match sustainability goals. The groundbreaking design of the tanks was based on variable wall thickness, starting with thicker walls at the base which then shrank down in thickness at the top, optimizing the intended material usage [5]. Nevertheless, Dubai has a strategic plan to have 25% of its buildings 3D-Printed by 2030. To fulfil this plan, numerous projects were completed such as the pioneering 3D-printed drone research and development laboratory for the Dubai Electricity and Water Authority

(DEWA). The printing activity of the 168-square-meter lab was concluded in merely three weeks [6]. Furthermore, the wave-like walls of the data center completed by Peri utilizing COBOD's famous BOD 2 in 2023 proved the potential of the technology in creating unique architecture. This data center spanned 6,600 square feet and stands 30 feet high, and its distinctive walls were printed in merely 140 hours where maximum wall overhang of around 40 degrees were applied. The special concrete mix used in this data centre was provided by Heidelberg Materials through which carbon footprint was proven to be less by 55% when compared to traditional concrete mixes [7].

3. Rheology of 3D-Printable Concrete

Turning the dream of implementing 3D-Printing technique in mass-production construction projects into reality, requires that, the most famous construction material; Concrete, to be examined before, during and after being 3D-Printed. A thorough assessment of concrete properties in both fresh and hardened states is required. The feasibility of 3D-Printing Concrete depends on several process parameter namely, Material Discharge Rate, Nozzle Speed, Print Path, Layer height, layer width, targeted total height or total number of vertically deposited layers. In essence, all these process parameters can only be controlled through the material properties; specifically, Rheology of the 3D-printable Concrete. Nevertheless, 3D printable Concrete exhibits inconsistent rheological parameters, that need to be fulfilled within a limited time frame.

Before shedding more light on the rheological parameters that are of major concern to the applicability of 3D Printable Concrete, it is deemed necessary to talk about the successful properties of 3D-Printable Concrete mix for layer-deposition technique. In essence, three properties need to be attained: Printability, Extrudability and Buildability. A mix is considered extrudable when it can easily be discharged from the nozzle, while printability is governed through visual inspection of the printed filament making sure a continuous layer is being deposited with no filament tearing conforming to the preset printing parameters of the desired layer height and width. Nevertheless, buildability reflects the maximum height that could be reached through layer-deposition technique without failure. As a matter of fact, the underlying factors for success of a 3DCP mix is through controlling its rheological properties; namely, plastic viscosity and yield stress. Yield stress is typically classified of two states: Static and Dynamic Yield stresses. The Static Yield stress can be identified as the minimum stress to be overcome for initiation of flow to take place. While Dynamic stress can be defined as the minimum stress required to keep the flow. Nonetheless, the plastic viscosity is the resistance to deformation as dynamic yield stress is exceeded. As a matter of fact, one important factor in the rheology of cementitious materials, especially concrete and mortar, is static yield stress. This characteristic is connected to the development of early hydration products and particle flocculation, which lead to the structural build-up of materials at rest. The microstructure of the material stiffens during rest, increasing the static yield stress. This tendency, wherein the material's yield stress rises with resting time, is explained by the thixotropy phenomenon. Thixotropy is a time-dependent shear-thinning behavior exhibited by cementitious materials. In other words, a Thixotropic material shows a drop in viscosity under shear and recovers its former structure when left rest. The reversible structural build-up that occurs at rest is the primary attribute of thixotropy in cementitious materials. This behavior can be measured using a variety of thixotropic indices, such as the structural build-up rate (Athix) [8]. The static yield stress of concrete denotes its ability to resist deformation under low stress conditions. Higher static yield stress indicates that the concrete can resist flowing or segregating when at rest, which is critical for maintaining stability and shape retention in 3DCP applications.

In the case of 3DCP, once the mix is discharged out of the nozzle, the material remains at rest. The great attention given to the structuration rate has led to the development of models quantifying the thixotropic behaviour through monitoring the way a material structure evolves over time at rest. Such models aid engineers and material scientists in optimizing concrete mix designs to attain the desired balance between workability and stability. One of the models quantifying the rate at which the static yield stress can evolve at rest is presented in. Eq. (1) adopted from Roussel [9] is shown below:

$$\tau = \tau_0 + A_{thix}t \qquad \text{Eq. (1)}$$

where, τ = shear stress (Pa)

τ_0 = static yield stress (Pa)
A_{thix} = Rate for structuration of cement paste or concrete (Pa/s)
t = time (s)

A higher structuration rate means that the mix can rapidly regain its yield stress after being disturbed, or once the external external force exerted on the material is removed. For 3DCP to be successful, its static yield stress growth rate must be compatible with the required buildability rate and the desired material extrusion rate. The higher the structuration rate, the higher is the total build-up height achieved. However, the buildability rate needs to be bound by a limit to avoid formation of cold joints or interlayer bond strength. Nonetheless, extrudability and pumpability of 3DCP requires the static yield stress of the mix to be quite low so the required pumping pressure is relatively low. However, the 3DCP mix needs to be able to recover back its static yield stress once deposited and extruded out of the nozzle in a timely manner so that it can hold its own self weight and hold the weight of the subsequent layers that will be deposited on it. For a smooth flow inside the hose, the dynamic yield stress and plastic viscosity needs to be sustained at relatively low values to avoid blockage of the hose.

The inconsistent rheological properties of 3DCP necessitates the timely transition from dynamic stress inside the hose to static yield stress once the layer is deposited on the allocated surface. This transition control needs to be in coordination with the extrusion rate of the material from the nozzle to ensure printability of the mix.

3D Printing in construction is globally recognized as a sustainable approach to automate the industry while minimizing waste, accident rates and human intervention. 3D-Printable Concrete has gained popularity because it maintains the fundamental constituents of traditional Concrete. It uses the same components found in standard concrete mixes, including cement, aggregates, sand, water, and a few secret chemical admixtures doing the magic, turning it into the printable version through regulating its rheological properties. Researchers have dedicated years to analysing the layer-deposition technique, linking it to material rheology while examining printing parameters and various types of printers available in the global market. These contributions from the literature have significantly enhanced our understanding of 3D printing in construction. However, there is a need to focus on further improving the sustainability of this technology. Concrete being used, with huge amounts of Cement involved in 3DCP cannot be considered an environmentally friendly material, since production of Cement is accountable for around 8% Carbon dioxide (CO_2) gas emissions [10] Optimizing the mix composition to incorporate more naturally existing by-products, or recycled waste byproducts through cradle-to-cradle approach as SCMs would be the best way forward to further enhance the sustainability aspect of 3D-Printing in Construction. Nonetheless, the commonly used industrial by-products like Fly Ash need to be replaced as more coal stations are being shut down. Thus, interest has increasingly towards finding abundant resources for pozzolanic SCMs such as agricultural waste by-product containing considerable amount of amorphous silica. Nevertheless, Calcined Clay or Metakaolin has recently gained popularity for being used as an SCM being an alumino-silicate exhibiting a filling effect and a progressive pozzolanic activity leading to increase of green strength of the Concrete mix and the corresponding mechanical properties [11].

In this paper, a comparative analysis on the structural build-up rate of various Concrete mixes incorporating different SCMs at selective dosage rates will be presented. The experimental method used to measure the static yield stress growth rate is the Stress-growth method.

4. Methodology and Experimental Setup

In this paper, the static yield stress evolution rate is measured through the Stress-growth method with the help of Shear Vane Apparatus that is typically used in Soil Measurements. Fig. (1) below shows the shear vane apparatus involved. A constant rotational speed is applied to the single cell which is loaded with prepared Concrete mixes. Concrete is mixed by hand to prepare batches of 2 litres. Various samples were taken from the original Concrete mix prepared at time, t_0. Test was done at 15 minutes interval to monitor the progressive yield stress evolution rate. The maximum torque attained at the end of the test duration is used to derive the static yield stress value at that specific time via considering the shear surface area and the vane dimensions. Eq. (2), (3) and (4) were used for calculation purposes. The static yield stress values are plotted against time (t) which reflects the paste age measured since stoppage of mixing.

Fig.1: Laboratory Scale Shear Vane Apparatus

$K = \Pi * D^2 H / 2 * 10^{\wedge 6} [1 + D/3H]$, Eq. (2)

D = measured diameter of the vane, mm, H = measured height of the vane, mm.

$T = \Delta / B$ Eq. (3)

T= Torque (N.m), B=slope of calibration curve in (°/N.m), Δ = deflection in degrees

τ = Static yield stress, $\tau = \Delta * b * k$, $b = 1/B$, N.m/°, $k = 1/K$, m^{-3} Eq. (4)

Fig. 2 below represents the slope of the calibration curve for the used spring. Spring No. 1 was used with the largest vane available in the lab whose D = 25.4 mm and its H = 25.4 mm as presented in Fig. 3. Measurements of the vane size were taken using the vernier caliper tool.

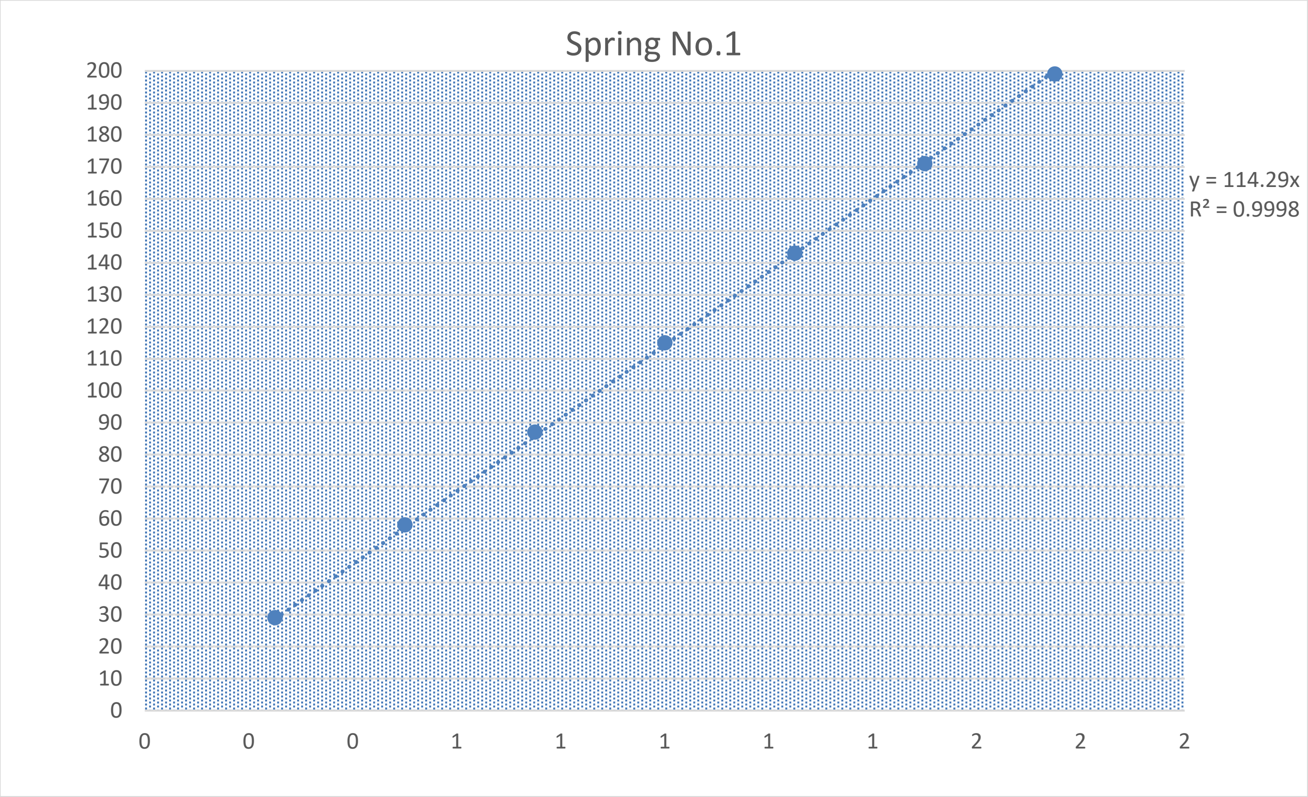

Fig. 2 Calibration Chart for Spring No. 1

Fig. 3 Shear Vane used in the test setup

In rheological measurements, the vane geometry provides several noteworthy benefits that improve data collecting accuracy and dependability, especially for materials with complex flow characteristics [12].

1. **Improved Shear Uniformity:** The material is sheared along a cylindrical surface that the vane circumscribes. In comparison to alternative geometries, this design guarantees a more equal distribution of shear throughout the sample leading to a more uniform shear profile throughout the material.
2. **Mitigation of Slip Flow Issues:** The phenomena of slip flow, in which the material adheres improperly to the measuring surface leading to inaccurate measurements, is a significant challenge in rheological measurements. The vane geometry minimizes slip problems since shearing takes place inside the material and not at the material-surface interface. This internal shearing motion introduced by the vane and its special geometry ensures that the measurements better reflect the sample's rheological characteristics by eliminating the issues related to slip flow.
3. **Minimal Sample disruption:** The vane is gently introduced into the sample, resulting in the least amount of material disruption prior to taking any measurement. When assessing thixotropic suspension specifically Concrete mixtures materials which exhibit shear thinning behavior—this is specifically crucial. Any pre-measurement disruption or pre-shearing history introduced can drastically alter the behavior of such materials and produce incorrect data.
4. **Consistency:** More consistent results across samples are a result of the uniform shearing action applied to the multiple samples involved.

In summary, the vane design offers a more accurate depiction of the material's actual rheological properties by minimizing slip and disruption and facilitating uniform shear action into the various samples. This is particularly significant in studying thixotropic suspensions like Concrete. Specifically, where the results might be greatly influenced by the interaction between the materials and the involved measurement apparatus. This improved measurement accuracy and precision offers enhanced comprehension and characterization of material behavior under different circumstances.

5. Accuracy of results

The shear vane apparatus provides a practical and relatively quick method for estimating the static yield stress of fresh concrete. However, accuracy and reliability of its results can be compromised due to various factors specifically, the variations of the test setup and operator dependency. To improve reliability, shear vane readings could be validated against slump flow tests and correlation between both tests should be monitored.

6. Materials Used

The purpose of this study is to test 3DCP mixes made with materials that can be used in lieu of cement and to compare the effects of varying the dosage at which each suggested SCM is replaced to find the most environmentally friendly mix possible.

The materials which will be used in this research are basically; Silica Fume, Metakaolin, biochar while incorporating two different types of superplasticizers, namely: PCE and Naphthalene-based Superplasticizers provided from Sika Egypt. It is necessary to mention that the Metakaolin used in this study is based on calcining Egyptian Kaolin coming from Kalabsha, at around 850°C for 2 hours. Although research on addition of Metakaolin to 3DCP mixes is quite limited, a recent study published by Duan et al. [13] stated that addition of 10% Metakaolin in 3DCP elevated its shear-thinning behavior and structuration rate increasing both the stiffness and early strength development of the mix. It has been reported in [13] that yield stress was increased by 285.54% and dynamic yield stress by 129.44% compared to the reference mixture. On the other hand, researchers had a great appetite for including silica fume in 3DCP mixes. And through literature, it has been found that Silica fume greatly accelerates the rate at which structural built-up takes place in 3D printed concrete mixes. Adding silica fume to the mixture accelerates the development of early strength because it promotes the formation of a denser microstructure. This is because cement paste's calcium hydroxide and silica fume react pozzolanic to produce additional calcium silicate hydrate (C-S-H), which is necessary for the growth of early-age strength [14]. Along with Metakaolin and Silica Fume, biochar is also introduced in the Concrete mixes being tested for the purpose of this study. Biochar is defined as the substance rich in carbon when organic biomass is pyrolyzed, typically in a special furnace without oxygen. The significance of adding biochar in Concrete mixes is linked to Circular economy and sustainability development goals through implementing the innovative technique of waste management through the pyrolysis technique. Nevertheless, Biochar is considered part of the biological cradle-to-cradle cycle and is famed for its carbon-sequestration ability once added to the Concrete in replacement of Cement. Hence reducing the environmental impact of the construction industry, given that Cement is held accountable for 5-7% of CO_2 emissions worldwide [8].

7. Opportunities and Concerns

Progressive involvement of 3D-Concrete printing in the construction industry offers a multitude of benefits while also projecting various challenges that need to be attentively addressed.

Opportunities offered by 3DCP in construction can be listed below:

- Reduced Labor Force
- Lowered Human Intervention
- Minimized Material Waste
- Reduced Transportation costs specifically with onsite
- Freedom of design and User-Customization allows pioneering in the architecture and construction sector.

However, challenges of mass-production using 3DCP persist. Around the globe, 3DCP has gained popularity for standing out in stand-alone projects. The following concerns hurdle the expanded use of 3DCP at a substantial scale:

- Higher initial investments of 3DCP in the budgeting exercises of construction projects.
- Liquifying the depreciation costs for the 3DCP machinery remains an open question for many contractors and developers in the market.
- Life-time expectancy and maintenance or repair costs of 3DCP machines remain unknown and cannot be related to a database of executed large-scale projects globally.
- Developing 3DCP mixes remains challenging as close monitoring of inconsistent rheological properties is deemed necessary, and highly trained technical expertise is further required for mix optimization.
- Widely incorporated 3DCP mixes still use relatively high Cement content, which negatively impacts its introduced sustainability edge.
- The merging of this automated technology with the traditional construction methods. 3DCP is still used for building the vertical walls of a certain structure, while conventional methods must be followed for executing foundations, slabs and beams.
- Most 3DCP vertical walls are not load-bearing and traditionally reinforced columns are still used to ensure the structural integrity of the building.
- Merging the printing activities along with the traditional construction activities presents a challenge for precisely managing the overall project timeframe specifically if the printer operation exists on the critical path of the designated project schedule.

In summary, the construction industry should be more attracted to the numerous advantages offered by 3DCP. Nevertheless, further studies need to thoroughly tackle the concerns associated with technology to turn it into a more viable and highly competent construction method.

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