RHEOLOGY AND PRINTABILITY OF ENGINEERED CEMENTITIOUS COMPOSITES-A LITERATURE REVIEW

YIWEI WENG
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

BING LU
Singapore Centre for 3D Printing and School of Civil and Environment Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

MING JEN TAN
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

SHUNZHI QIAN
Singapore Centre for 3D Printing and School of Civil and Environment Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

Abstract
Additive Manufacturing (AM), normally known as 3 Dimensional Printing (3DP), is one of many manufacturing processes in the field of Rapid Prototyping (RP). In 3DP process, the solid part is built by adding layers of materials sequentially. Compared to traditional manufacturing technologies, 3DP has attracted more and more attention in many fields, including building and construction, attributed to its advantages such as greater flexibility on constructing geometrically complicated structures, greatly improved efficiency, reduced onsite labor requirement and less waste generated.

Engineered Cementitious Composites (ECC) is a cementitious composite material reinforced with randomly distributed short fibers. It has great potential to be used in building and construction as well as 3D printing field due to its unique mechanical properties. Rheological property is an essential parameter affecting the printability of ECC during printing process. This article surveys the literatures on ECC, followed by a brief introduction of developments in 3DP field. The methods to improve the rheological property of ECC are discussed thereafter. In the last section, challenges on ECC printing are discussed from aspects of rheology control and printability.
KEY WORDS: 3D printing, Engineered Cementitious Composites (ECC), rheology control, printability

1. INTRODUCTION

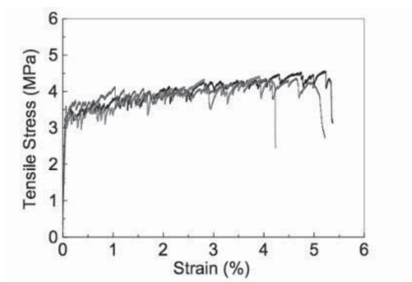
1.1 Engineered Cementitious Composites (ECC)

Concrete is one of the most widely used construction materials in the world. It possesses many excellent properties, such as convenience in application, wide raw material sources and generally highly reliable performance, making it a key structural material in modern civil engineering(Mehta and Monteiro, 2006). In United States alone, concrete industry represents a €23.3 billion of sales per year(Silva et al., 2015).

Proc. of the 2nd Intl. Conf. on Progress in Additive Manufacturing
Edited by Chee Kai Chua, Wai Yee Yeong, Ming Jen Tan, Erjia Liu and Shu Beng Tor

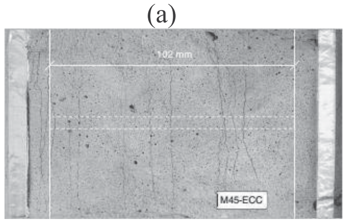
Published by Research Publishing, Singapore
ISSN: 2424-8967

With all aforementioned advantages, conventional concrete is however a brittle material with low tensile strength and crack resistance, which limits its further engineering applications(Li, 2011). Li and Leung (1992) proposed micromechanics based design theory for a novel ductile concrete termed as Engineered Cementitious Composites (ECC)(Li and Leung, 1992). It has similar mechanical strength to conventional concrete in all aspects except for tensile properties (Li and Kanda, 1998). Unlike normal concrete which is brittle and prone to cracking, ECC is a special class of concrete with high tensile ductility and toughness. The ultimate tensile strain of the ECC ranges from 3% to 5% under uniaxial tension tests. After initial cracking in the matrix, ECC can sustain higher level of loading with strain-hardening behavior. Multi-cracking pattern is observed, and cracks in ECC can be effectively controlled under 60 μm (Zhang et al., 2011). The unique mechanical property makes ECC a potential high performance material to be used in building and construction as well as 3D printing. Figure 1 (a,b,c) show the tensile strain-hardening behavior and ultra-ductility of ECC, the ECC under four-point bending test and multi-cracking pattern of ECC, respectively.



(a)

(b)



(c)

Figure 1 Characteristic mechanical property of ECC: (a) Strain-hardening curve(Li 2002); (b) ECC under four-point bending test ;(c) Multi-cracking pattern of ECC(Ranade et al., 2014)

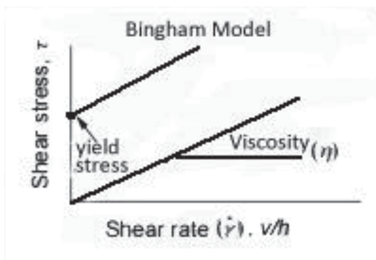
1.2 3D printing technology

3DP is a manufacturing technology which fabricates the solid part layer by layer(Groover, 2007). It has attracted attentions in many fields, including building and construction due to its advantages over tradition manufacturing technology, such as shortened lead-time, flexibility in producing complex shape etc. Researchers in building and construction sector have attempted various 3D printing technologies, such as Contour Crafting.(Khoshnevis et al., 2006), D shape and Concrete Printing(Lim et al., 2012).

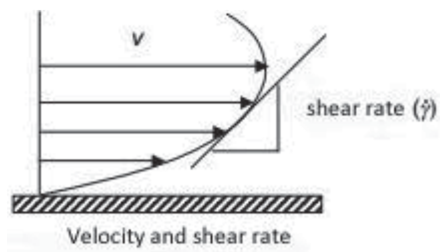
1.3 Rheological property

During printing process, proper control of rheological property is critical in ensuring smooth flow during pumping and rapid setting of the concrete after extruding/printing.

Classic Newtonian fluid, like water, is characterized by a single coefficient of viscosity at a specific temperature. Though the viscosity changes with temperature, it does not change with the shear rate(Lavrov, 2012). The large class of fluids that the correlation between shear stress and shear rate is not linear are called non-Newtonian fluids. The simplest and commonly-used model to describe the rheological property of concrete is Bingham Model, as shown in Figure 2(a).



(a)



(b)

Figure 2. (a)Bingham Model; (b) Schematic of shear rate

The Bingham model can be described as below(Banfill, 2011)

$$\tau = \tau_0 + \eta\dot{\gamma} \quad (1)$$

Where $\tau_0$is the yield stress at which a material begins to deform plastically, η is the viscosity which describes the resistance to flow, and $\dot{\gamma}$ is the shear rate that is velocity gradient between the adjacent fluid layers as shown in Figure 2(b). For fluid, yield stress is the shear stress needed to start moving concrete. In 3D printing process, the viscosity should be low initially, then rise up promptly to ensure enough green strength to support the self-weight of the printed structures. In the following section, methods to control rheological property and challenges of ECC printing are discussed.

2. METHODS TO CONTROL RHEOLOGICAL PROPERTY

Many researchers try to control rheological property of concrete via modifying mix design. Slag is a kind of replacement material of cement. Incorporating slag with an optimum content of 15% by mass in concrete can increase the workability of concrete via decreasing the dosage of cement (Boukendakdji et al., 2009) . Concrete is considered as a two-phase material, consisting of coarse aggregate (CA) and mortar. Higher content of CA and finer aggregates normally result in higher concrete rheological parameters, namely higher yield stress and viscosity(Hu and Wang, 2011). For ECC, increasing the water-binder ratio and high range water reducer(HRWR)-binder ratio results in a reduction in plastic viscosity and relative yield stress, relatively (Yang et al., 2009). M. Li and V. Li demonstrated that strong correlation existed between plastic viscosity, PVA fiber dispersion and ECC composite behavior (Li & Li, 2013).

It is also possible to control rheological property of concrete by changing the mixing method. Delaying the admixtures addition (melamine formaldehyde sulfonate and naphthalene formaldehyde sulfonate) increases the workability than that of simultaneous addition(Aiad et al., 2002). Furthermore, using high shear rate mixing leads to improved flowability (lower viscosity) (Williams et al., 1999). Also, yield stress can be reduced to about a half by vibration than that without vibration, but little influenced the plastic viscosity(Hu and de Larrard, 1996).

Addition of some admixtures can also be used to modify the rheological property. Addition of superplasticizer reduces yield stress, but the reduced water content increases the plastic viscosity resulting in mixes which are sticky and difficult to handle(Banfill, 2011). Mineral admixtures have certain impact on the viscosity of cement paste and concrete. Ultrafine fly ash is considered as the best mineral admixtures that reduce the yield stress and viscosity among six different mineral admixtures including coarse fly ash, fly ash, fine fly ash, ultra-fine fly ash, metakaolin and silica fume(Ferraris et al., 2001). Compared to the case of no silica fume addition, mixing silica fume in concrete decreases the workability due to higher surface areas of silica fume particles (Nochaiya et al., 2010).

3. CHALLENGES OF PRINTABILITY OF ECC PRINTING

For common 3D concrete printing process, raw materials are mixed in the mixer firstly. Then, they are moved to container and subsequently to nozzle through delivery system. The concrete are printed out upon reaching the nozzle layer-by-layer to form the solid part. One example of whole printing system is shown in Figure 3(Le et al., 2012)

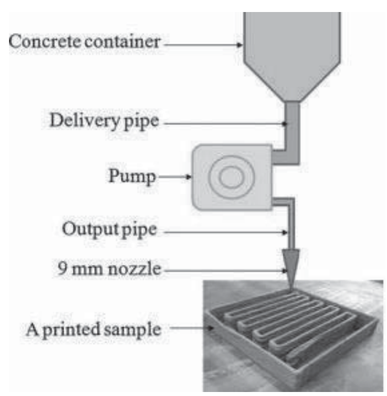


Figure 3 Schematic of concrete delivery system(Le et al., 2012)

As discussed before, the rheological behavior of concrete can be described as Bingham Model. Applied shear stress (e.g. translated from pressure of the air pump) should be more than the yield stress to ensure smooth flow so that the delivery and nozzle system will not be blocked. Furthermore, after concrete is printed out from nozzle, it must be capable of rapidly increasing viscosity to avoid severe slumping. In addition, open time, an important measure for the working window of the material, is also a parameter controlled by the viscosity dynamics of the concrete.

Pumpability refers to how well the freshly mixed concrete can be transported from the container to the nozzle. During the entire flow process, the concrete should be kept at low viscosity value to flow smoothly in the delivery system. In addition, the concrete should avoid hardening and blocking the pipe. Therefore, the rheological property of fresh concrete is an important parameter which should be considered during the pumping process. Thus, in this process, researchers should consider to decrease the viscosity of concrete via the methods discussed in Section 2.

Buildability is also an essential property of printable ECC. After concrete printed out from the nozzle, it should have enough green strength supporting its weight to avoid slump. The viscosity dynamics should be thoroughly studied so that a timely increasing of viscosity can be achieved via many methods e.g. addition of accelerators or rapid hardening cements.

4. FUTURE PROSPECTIVE AND CONCLUSION

This article reviews the literatures of concrete printing. ECC, 3DP and rheology are briefly introduced in the first section, followed by methods to control the rheological property of concrete in Section 2. Several parameters related to rheological property control in concrete printing are discussed in the third section.

Rheological property of concrete is an essential factor affecting concrete printing. In future research, it is suggested to attempt different methods to control the viscosity for printing, such as changing mixing method, different admixtures, etc.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the National Research Foundation.

REFERENCES

Aiad, I., El-Aleem, S.A. and El-Didamony, H. (2002). Effect of delaying addition of some concrete admixtures on the rheological properties of cement pastes. *Cement and Concrete Research*, 32, 1839-1843.

Banfill, P. (2011). Additivity effects in the rheology of fresh concrete containing water-reducing admixtures*. Construction and Building Materials*, 25, 2955-2960.

Boukendakdji, O., Kenai, S., Kadri, E. and Rouis, F. (2009). Effect of slag on the rheology of fresh self-compacted concrete. *Construction and Building Materials*, 23, 2593-2598.

Ferraris, C.F., Obla, K.H. and Hill, R. (2001). The influence of mineral admixtures on the rheology of cement paste and concrete. *Cement and concrete research*, 31, 245-255.

Groover, M.P. (2007). Fundamentals of modern manufacturing: materials processes, and systems, John Wiley & Sons.

Hu, C. and de Larrard, F. (1996). The rheology of fresh high-performance concrete. *Cement and concrete research*, 26, 283-294.

Hu, J. and Wang, K. (2011). Effect of coarse aggregate characteristics on concrete rheology. *Construction and Building Materials*, 25, 1196-1204.

Khoshnevis, B., Hwang, D., Yao, K.-T. and Yeh, Z. (2006). Mega-scale fabrication by contour crafting. *International Journal of Industrial and Systems Engineering*, 1, 301-320.

Lavrov, A. (2012). Non-Newtonian fluid flow in rough-walled fractures: A brief review. *Dynamic Web Programming and HTML5*, 363.

Le, T.T., Austin, S.A., Lim, S., Buswell, R.A., Gibb, A.G. and Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and structures*, 45, 1221-1232.

Li, V.C. and Kanda, T. (1998). Innovations Forum: Engineered cementitious composites for structural applications. *Journal of Materials in Civil Engineering*, 10, 66-69.

Li, V.C. and Leung, C.K. (1992). Steady-state and multiple cracking of short random fiber composites. *Journal of Engineering Mechanics*, 118, 2246-2264.

Li, Z. (2011). *Advanced concrete technology*, John Wiley & Sons.

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G. and Thorpe, T. (2012). *Developments in construction-scale additive manufacturing processes. Automation in construction*, 21, 262-268.

Mehta, P. and Monteiro, P. (2006). Utilization of palm oil fuel ash in concrete: a review. *Concrete-Microstructure, Properties and Materials.*

Nochaiya, T., Wongkeo, W. and Chaipanich, A. (2010). Utilization of fly ash with silica fume and properties of Portland cement–fly ash–silica fume concrete. *Fuel*, 89, 768-774.

Ranade, R., Zhang, J., Lynch, J.P. and Li, V.C. (2014). Influence of micro-cracking on the composite resistivity of engineered cementitious composites. *Cement and Concrete Research*, 58, 1-12.

Silva, F.B., Boon, N., De Belie, N. and Verstraete, W. (2015). Industrial application of biological self-healing concrete: challenges and economical feasibility. *Journal of Commercial Biotechnology*, 21.

Williams, D.A., Saak, A.W. and Jennings, H.M. (1999). The influence of mixing on the rheology of fresh cement paste. *Cement and Concrete Research*, 29, 1491-1496.

Yang, E.-H., Sahmaran, M., YINGZI, Y. and Li, V.C. (2009). Rheological control in production of engineered cementitious composites. *ACI Materials Journal*, 106, 357-366.

Zhang, J., Leung, C.K. and Gao, Y. (2011). Simulation of crack propagation of fiber reinforced cementitious composite under direct tension. *Engineering fracture mechanics*, 78, 2439-2454