PROPERTIES OF 3D PRINTABLE CONCRETE

GIDEON P.A.G. VAN ZIJL
Civil Engineering, Stellenbosch University, Corner of Banhoek and Joubert Streets,
Stellenbosch 7600, South Africa

SUVASH CHANDRA PAUL
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang
Technological University, Singapore

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

ABSTRACT: Different manufacturing processes demand appropriate materials processing adjustments. This holds true for concrete materials that have versatility in processing, including normal mixing and casting in the construction industry; spraying or so-called shotcrete application in soil stabilization for mining or construction excavations, extrusion in pre-casting factories for structural elements intended for the construction industry; and spinning manufacturing processes for concrete pipes. Recent innovation in 3D printing for construction demands yet another adaption of the mix design and manufacturing process. This paper presents an overview of required adaptions in terms of mix ingredients and mixing process and equipment to produce the appropriate rheology in the fresh state, rate of viscosity change for dimensional stability, sufficient adhesion/cohesion for interlayer bond, and appropriate, specified hardened and fresh rheology. Attention is given to fresh rheology and the chemical additives to prevent ingredient segregation during mixing and processing, despite a range in fluidity required by the various processes from highly workable for pumping, to dough-like consistency for extrusion and 3D printing.

Keywords: concrete, deformability, extrusion, printing, SHCC.

INTRODUCTION

Whilst virtually all structures and structural forms can be produced by standard mixing, moulding and in-situ placement of concrete manually, various manufacturing processes have been developed to address the level of geometrical complexity, construction sequence and speed, logistics on congested construction sites, quality, and labour issues. Apart from overcoming limits of manual placement or lack of labour, cost finally drives the choice of manufacturing method. Cost models should be holistic and include labour, transportation, energy consumption and emissions. In addition to up front manufacturing costs, overall life cycle cost should be considered. The emphasis on reduction of construction time and production costs has profound influence on construction process that has led researchers to explore 3D concrete printing.

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In turn, manufacturing processes may have distinct influence on concrete fresh and hardened properties. In modern concrete materials design it has become possible to design for specified performance, also keeping in mind the manufacturing process. Examples of mechanical consequences include the level of compaction, reduced entrained air through extrusion leading to increased strength and stiffness, and production-dependent fibre alignment in fibre reinforced concrete (FRC). Here, processes for structural element production of concrete materials potentially relevant to 3D printing are presented. Particular analogies exist between *extrusion*, *shotcrete* and 3D printing processes and are highlighted in the subsequent sections.

For robustness and sustainability, advanced concrete materials (ACM) and the use of waste streams as ingredient materials have been proposed for 3D concrete printing (Le et al. 2012; Malaeb et al. 2015; Laurent et al. 2014). In this paper, steel FRC (SFRC) and energy dissipating strain-hardening cement-based composites (SHCC) produced by extrusion and spraying are presented. The characteristics of these ACM might make them the material of choice.

EXTRUSION OF CONCRETE MATERIALS

Extrusion has clear relevance to additive manufacturing in the form of 3D printing, in final placement from a guided nozzle. This manufacturing method has been used extensively in the civil engineering construction industry in plants for pre-fabrication of structural elements varying from small decorative elements to large slab structural elements. In the next sections, material ingredient adjustments and hardened mechanical properties particular to extruded concrete are elaborated.

Mix adjustments for extrusion

Typical ingredients for concrete remain unchanged, namely cement, water and aggregate in the form of sand and larger stone particles. Strength is dominated by the water to cement mass ratio (w/c). Low w/c gives high strength and vice versa. In modern concrete industry it has become usual to include chemical additives in the form of superplasticisers (SP) and viscosity modifying agents (VMA, typically a methyl-cellulose**)**, and others like air entrainment agents (AEA), water repellence, etc. This may be done for particular required fresh or hardened concrete characteristics. However, it might simply be for cost reduction of the overall mix, or in consideration of the placement method or construction and procurement model. High strength concrete (HSC) and ultra-high performance concrete (UHPC) are virtually impossible to achieve without added SP. But, even in normal concretes it might turn out that reduced water content, the effect achieved by adding SP, leads to significant cement content, whereby significant cost saving is possible. Control of the amount of water in the mix might become important in cases of high water demand by for instance poorly graded, thus poorly packing sand, or aggregate with coarse texture.

The author's experience of extrusion is on SFRC and SHCC. For both these classes of materials it is usual to include SP and VMA even for normal mixing, casting and vibration of these concretes, for purpose of optimal dispersion of all heterogeneities including the fibre in the mix in the fresh state, and the VMA typically prevents segregation. For extrusion particularly, segregation of the various ingredients might occur due to high pressure build-up in auger-type or piston-type extruders, and subsequent segregation. In Figure 1 an unsuccessful extrusion exercise is depicted by only water exiting the extrusion nozzle! In fact, the pressure build-up can lead to equipment damage. It is recommended to adjust the VMA content, typically expressed as a % of cement mass, to produce the *dough-like* fresh consistence, but also producing homogeneous extrudates.

Mechanical performance of extruded concrete materials

Extrusion is a high pressure process, whereby mechanical properties of strength and stiffness of the concrete composite are altered. In SFRC, fibre alignment is also influenced by the extrusion methods.

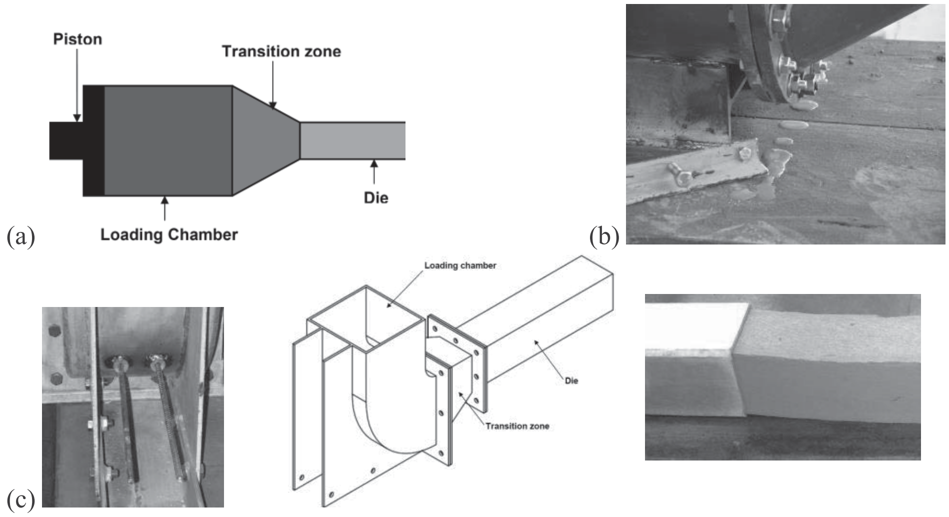

Figure 1. Piston-type extrusion shown (a) a piston extruder schematically, (b), pressure build-up and consequentially paste water drops only extruding, (c) a piston extruder with provision for steel reinforcement feeding into the extrudate (Visser 2007).

Strength and E-modulus of extruded concrete materials

Although the w/c ratio is dominant in determination of strength, it is well-documented that air entrainment reduces strength significantly. By high-pressure extrusion, air content is reduced and compressive strength increased. In FRC, another mechanism is modified, namely the efficiency of fibres through their alignment in the matrix. Figure 2 shows steel fibre orientation caused by extrusion, casting and a traditional concrete pipe-spinning fabrication method. It is clear that piston extrusion leads to fibre alignment in the actuator/piston direction, a random 3D orientation is typical from a standard casting process, and gravitational spread of fibres to the outer perimeter of the pipe wand is caused by rotational spin of the pipe mould in that manufacturing process. One-dimensional orientation of fibre is beneficial if this is exploited by the structural application. Figure 3 shows the force-deflection results of bending tests on extruded and cast SFRC plate specimens (De Koker 2004) both containing 3% by volume of 13 mm long, straight, 0.16 mm diameter medium strength (roughly 1.8 GPa yield stress) steel fibre. The significant increase in flexural strength is ascribed to the denser extruded matrix, higher matrix bond with steel fibre, and fibre alignment in the extruded specimens. Stiffness is improved by removal of entrained air in high-pressure extrusion. Visser & van Zijl (2007) reported a three times higher elastic modulus (E_c) for extruded versus cast SHCC plate specimens, with E_c^{cast} = 8-10 GPa and $E_a^{extrude}$ = 28.7 GPa (Visser & van Zijl 2007). It must be pointed out that this is an extreme example, and relatively high air entrainment in the cast SHCC specimens in the order of 10%.

Use of waste stream materials in extruded concrete materials

Where fly ash (FA) and slagment are available, these waste streams may be beneficial to concrete due to their pozzolanic effects, the fine particle size, and in the case of FA, the well-rounded particles beneficial for extruded SHCC (Peled & Shah 2003). Figure 4 shows tensile responses of SHCC with large (50% and more) cement replacement by FA, slagment from a local corex steel plant in South Africa, and a FA-slag blend (Gao Song & van Zijl 2004).

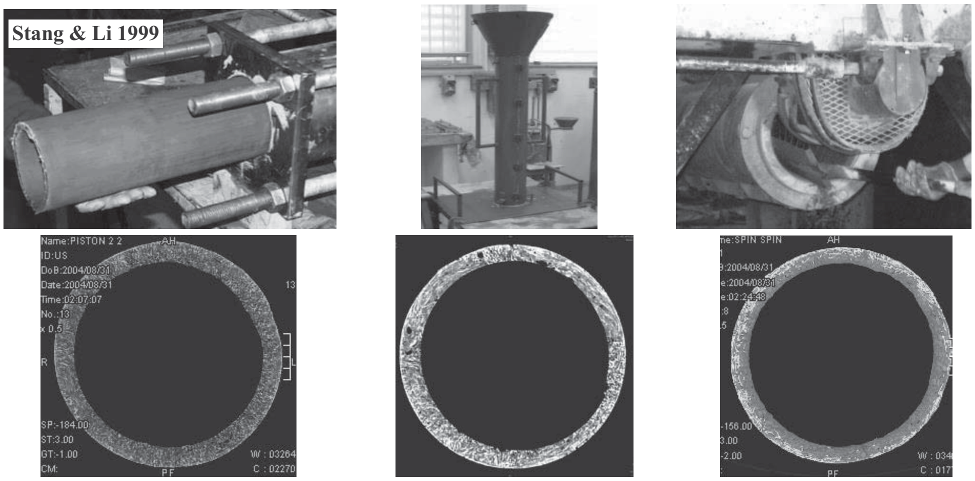

Figure 2. X-ray CT visualisation of manufacturing process influence on steel fibre orientation and dispersion, showing axially aligned fibre from piston-type extrusion (left), random orientation from casting and vibration (centre) and fibre gravitational dispersion to the outer perimeter in pipe spinning manufacturing. (De Koker 2004, Van Zijl 2005)

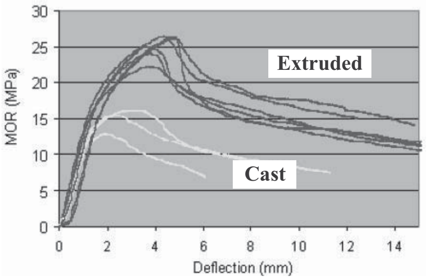

Figure 3. Load-deflection responses of SFRC for extruded versus cast beams (De Koker 2004).

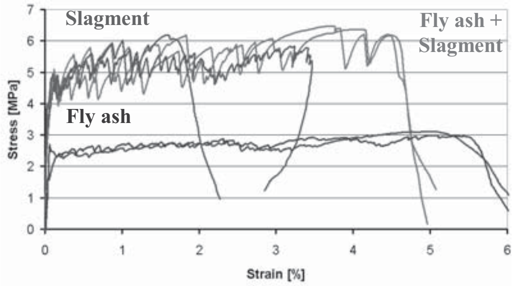

Figure 4. Influence of waste stream material on SHCC tension (Gao Song & van Zijl 2004).

SHOTCRETING OF CONCRETE MATERIALS

Sprayed application or shotcreting of concrete materials also requires adjustment of the mixture, in this case to adjust the rate of increased viscosity change to increase adhesion to stick to the surface, and to prevent run-off from sprayed surfaces. Figure 5 shows recent results of Stellenbosch University on deformability as a function of percentage calcium-alumina cement

(CAC) replacement of standard cement types. The type of CAC and percentage cement replaced were varied. CACs Ciment Fondu containing 34% alumina and Secar 51 with 51% alumina were used. The dosage of SP was adjusted to control the initial viscosity to achieve good mixing and sufficiently high slump flow for all mixes. A small slump cone of diameter d_0 = 100 mm was used to measure the flowability over time. In the slump tests, no external vibration was applied to consolidate the fresh SHCC. The maximum diameter of the spread d_1 and the diameter perpendicular to it d_2 were measured. The deformability (Γ) was then calculated as follows:

$$\Gamma = \frac{d_1 d_2 - d_0^{\ 2}}{d_0^{\ 2}} \tag{1}$$

The first slump flow value (t = 0 min) was taken directly after mixing and thereafter at fifteen minute intervals. The addition of the CAC decreases the slump flow. Higher dosages of CAC leads to a higher rate of deformability loss. The higher percentage aluminate content in Secar also leads to a higher rate of deformability loss than the Ciment Fondu for the same dosage. The reduced viscosity must be balanced by required open time (Le et al. 2012) in concrete printing. Figure 5c shows triplet shear responses of unreinforced load-bearing masonry (ULM) wall part with and without 10 mm shotcrete overlays, and a factor five increase in shear resistance of the latter.

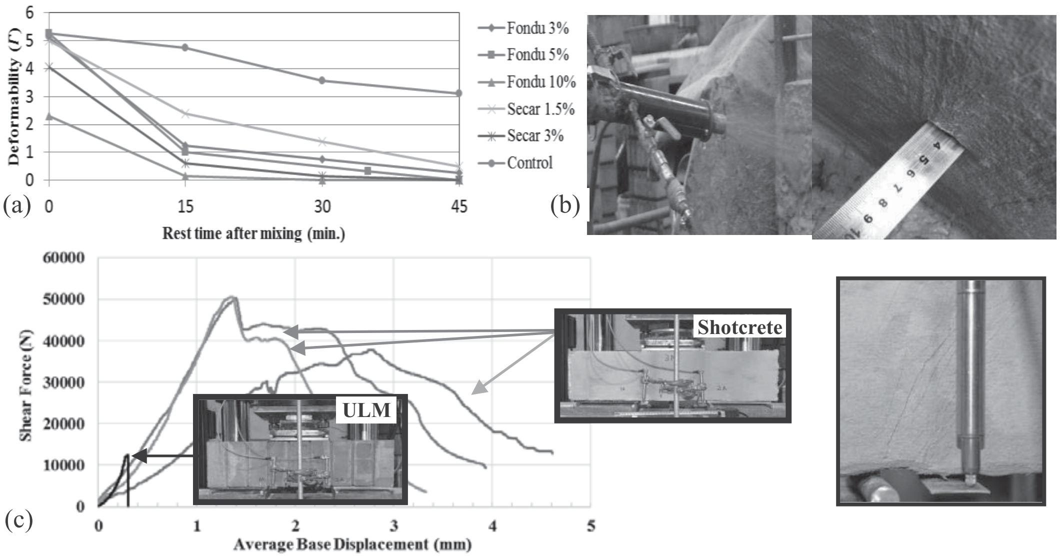

Figure 5. (a) Flowability of SHCC with lapse in time after mixing, as function of calcium-alumina cement content. (b) shotcreting of SHCC onto masonry and (c) triplet shear responses ULM with 10 mm shotcrete overlays on both faces, shown to be 5 times that of a reference ULM specimen.

SUMMERY AND CONCLUSION

3D printable concrete is a dough-like, no slump concrete. The current deposition method of this type of concrete is either extrusion or shotcrete. This paper has presented aspects for potential materials improvement, including the (i) use of viscosity modifying agent (VMA) to obtain the correct dough-like rheology but avoiding significant pressure build-up and associated segregation; (ii) low percentage calcium aluminate cement inclusion to improve interlayer adhesion and adjust viscosity development rate, which is to be balanced with open time. Manufacturing process influence on fibre alignment and air expulsion has been demonstrated.

In future current concrete construction technology may turn to automation by 3D printing to eliminate formwork and allow complex 3D geometries with minimal time and human interaction. For successful implementation and structural robustness, appropriate materials for their deposition or printing production system must be developed, learning from relevant analogous technologies of extrusion and shotcrete. It is imperative that characterisation of the hardened properties is performed to enable appropriate engineering design. Systematic application of these mix designs, with appropriate adjustments for local materials, cost and printer properties must follow, ensuring appropriate local material particles grading and rheological properties for extrudeability (ability to pass through a nozzle), buildability (ability to hold layered concrete), materials shear strength and hardening time with the ultimate aim of being able to design materials to specified behaviour in structural and architectural application through 3D concrete printing. Finally, in addition to the importance of material properties, a robust system is required for 3D concrete printing, with proper control to deposit this material accurately while retaining its desired engineering properties.

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