

Fabrication of Functionally Graded-cellular Structures of Cement-based Materials by Co-extrusion

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Abstract. Co-extrusion involves extrusion of multiple layers at the same time. Functionally graded materials comprising various layers with different properties can be produced through co-extrusion. Rheological control is vital for successful co-extrusion of layered cement-based materials. The paste flow in the barrel and the die land in a ram extruder should be plug-like, while the paste should be sheared and uniformly elongated in the die entry region. In this work, the rheology of the layered pastes was adjusted by changing the water content in each layer. An economical method using thin-wall tubes was effective to prepare layered feedrod of cementitious paste. The functionally graded cellular structures of cement-based materials were successfully fabricated by co-extrusion at a low extrudate velocity. Inspections showed that the roundness perpendicular to the extrusion direction, and the straightness parallel to the extrusion direction between layers were well preserved after extrusion. The transition between layers was gradual, which is critical for functionally graded materials.

Keywords: Co-extrusion, cement-based materials, functionally graded cellular structure

INTRODUCTION

One big disadvantage of concrete in use is its high density, typically 2300 kg/m^3 . In order to overcome this problem, light-weight concrete has been manufactured using either aeration or light-weight aggregates [1-4]. However, light-weight concrete is usually associated with high permeability and low strength. *This investigation will utilize an advanced co-extrusion process to produce functionally graded cellular microstructures which are highly porous in the center and becomes increasingly denser toward the surface.* The microstructure can be engineered to make the product light-weight while without sacrificing permeability and strength.

Extrusion is a process in which a stiff plastic paste is forced to pass through a rigid die where high shear produces fluid behavior. Co-extrusion involves extrusion of multiple layers. A very low water to cement ratio is used, which is beneficial to the ultimate strength of the extrudates. The high shear during extrusion improves bonding between layers. Extrusion has been successfully applied in production of many cement-based products, e.g., pressure pipe [5], plate [6], and fiberboard [7]. Extrusion can also be used to manufacture complicated shapes [8]. Extrusion has been shown to enhance performance, providing higher toughness, tensile strength and flexural strength [9, 10].

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Successful extrusion requires the paste to be soft enough to flow through the die while stiff enough to maintain its shape after extrusion. The paste should not undergo phase migration under high extrusion pressure. In addition, the extrudate should have minimum surface defects. All these requirements can be achieved by controlling the paste rheology. Rheology control is more critical in co-extrusion. Rheology among different layers should be matched for successful co-extrusion. Otherwise, the layers will be disturbed during co-extrusion. The extrudate velocity plays an important role as well. Too high velocity generates laminar or turbulent flow, which is not wanted in co-extrusion. Ideally, paste flow in the barrel and the die land in a ram extruder should be plug-like, while the paste should be sheared and uniformly elongated in the die entry region.

This paper focused on the fabrication of cementitious mixtures with functionally graded cellular structures using co-extrusion of layers with different porosities. The structure of extrudates was examined by optical microscope and scanning electronic microscope.

EXPERIMENTAL

Materials

A Type I cement (Essroc Cement Corporation) was used in all cementitious mixtures. Methyl hydroxyethyl cellulose (MHEC in short, WALOCEL M-20678 by Wolff Cellulosics) was employed to make extrudable dough-like pastes. Cenospheres, which are hollow particles of fly ash, (XL-150 by Sphere Services Inc., mean size 63 μm , specific density 0.57 g/cm^3), were blended into the mixtures to produce pores.

Mix Proportions

The compositions of the layered extrudates are listed in TABLE 1. Extrudates with 3 and 5 layers were fabricated respectively. The water content of the outermost layer was fixed. The water content of the remaining layers was adjusted until the co-extrusion was successful. The final values for the water content are shown in TABLE 1. The MHEC content changed with the change of water content so that the MHEC concentration in water was constant.

TABLE 1. Compositions of Layered Extrudates

No. of layers	Layer	Cement (g)	Cenosphere (g)	Water (g)	MHEC (g)	MHEC (% based on water)
3	Core	70	30	38	1.65	4.35
	Middle	90	10	28	1.30	4.35
	Outer	100	0	25	1.09	4.35
5	Core	50	50	45	1.96	4.35
	2nd	70	30	38	1.65	4.35
	3rd	80	20	34	1.48	4.35
	4th	90	10	28	1.30	4.35
	Outer	100	0	25	1.09	4.35

Mixing Procedure

The solid powders (cement, MHEC and cenosphere when used) were first dry mixed for 3 minutes at low speed using a planetary mixer (Model N-50, Hobart Corporation). Water was then added and the mixture continued to be mixed at low speed until a dough-like paste was formed. The dough-like paste was further mixed at higher speed for 1 minute.

Ram Extruder

The ram extruder shown in FIGURE 1 was used to fabricate the functionally graded cellular products. The piston was connected a 10-kN Instron load cell. The barrel had an inner diameter of 60 mm and a height of 150 mm. The die had an inner diameter of 12 mm and a length of 96 mm.

As the piston moves downward, the paste inside the barrel is forced into the die and the extrudate comes out the die exit. A static zone where the paste is not squeezed out forms a natural cone near the die entry region. In co-extrusion, extrudate with good quality was obtained once the static zone was formed and the flow was steady.

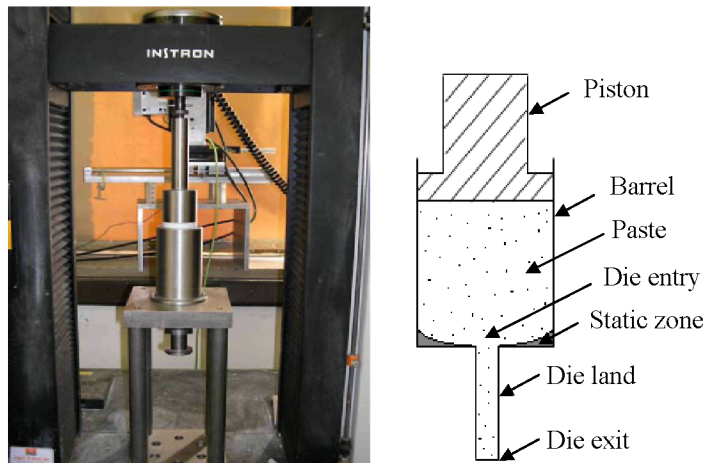


FIGURE 1. Ram Extruder. Left: Set-up of the Real Ram Extruder; Right: Schematic Illustration of the Ram Extruder.

CO-EXTRUSION OF CELLULAR GRADED STRUCTURES

A simple and cost-effective molding method was employed to make the layered feedrods. The molds are rods, thin-walled tubes, and alignment jigs, as shown in FIGURE 2.

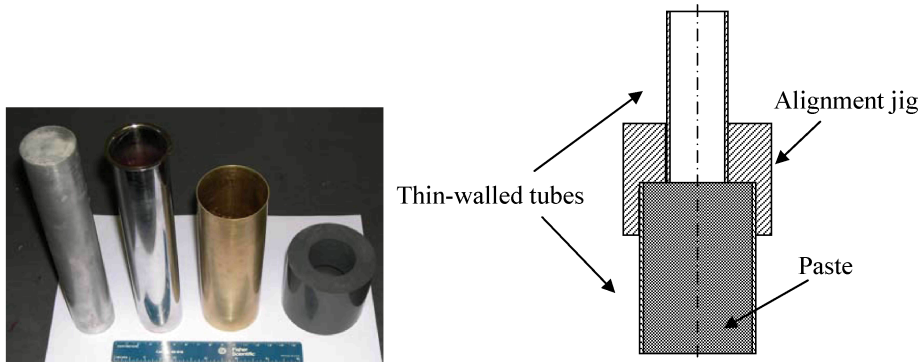


FIGURE 2. Molds for Making Layered Feedrod.

FIGURE 3 shows the preparation process of layered feedrod. First, the innermost paste rod was prepared using the smallest tube. The next paste rod was then made using a bigger tube. A hole was drilled in the bigger paste rod using the smallest tube and the innermost paste rod was inserted into the hole to make a two-layer feedrod. Feedrods with more layers can be prepared by this method.

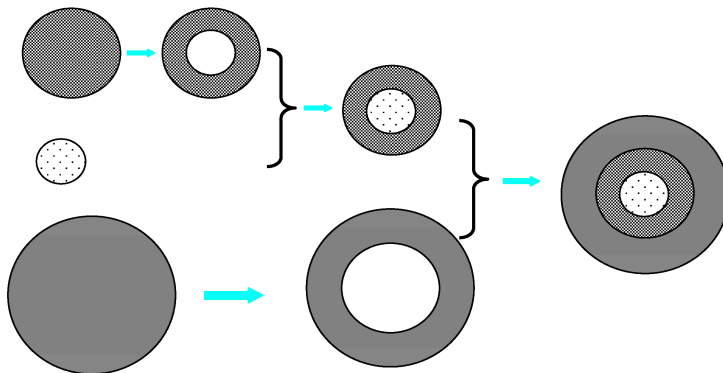


FIGURE 3. Schematic Diagram for Multiple-Layer Feedrod Preparation.

After all the layers were stacked, a multiple layered feedrod was prepared to be ready for extrusion. Extrudates with 3 and 5 layers were extruded respectively at extrudate velocity of 1.67 mm/s.

STRUCTURE EXAMINATION OF THE EXTRUDATES

Cross sections perpendicular and parallel to the extrusion direction were examined by an optical microscope at low magnification (FIGURE 4 and FIGURE 5). The artificial colors were used to highlight different layers of the extrudates. The photos indicate that the roundness perpendicular to the extrusion direction and the straightness parallel to the extrusion direction between layers were well preserved during extrusion.

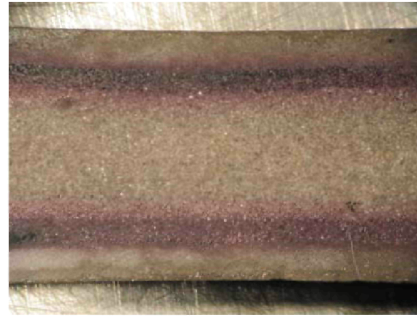


FIGURE 4. Cross Section of 3-Layered Extrudate. Left: Perpendicular to Extrusion Direction; Right: Parallel to Extrusion Direction.

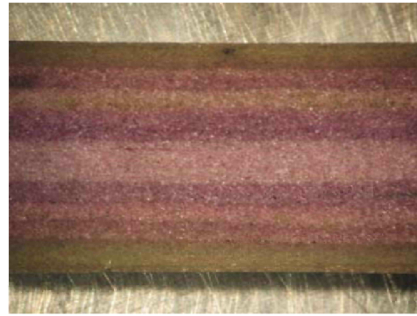
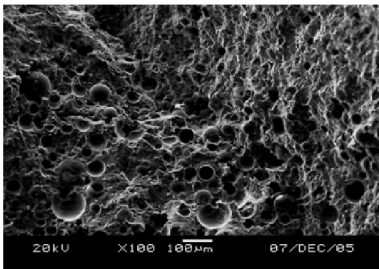
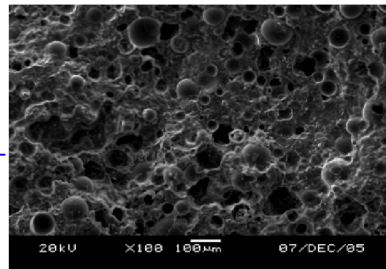


FIGURE 5. Cross Section of 5-Layered Extrudate. Left: Perpendicular to Extrusion Direction; Right: Parallel to Extrusion Direction.

The interfaces between layers for the 5-layer extrudate were further examined using a scanning electronic microscope (SEM, JEOL JSM-6060LV by Oxford Instruments). As seen in FIGURE 6, the cellular particles are embedded in the matrix of hydrated cement. The volume of the cellular particles increases progressively from the outer layer to the fifth layer. The interfaces are identified by changes in the volume of the cellular particles. There is no debonding between layers, which is good for functionally graded materials.



Outer
4th
4th
3rd



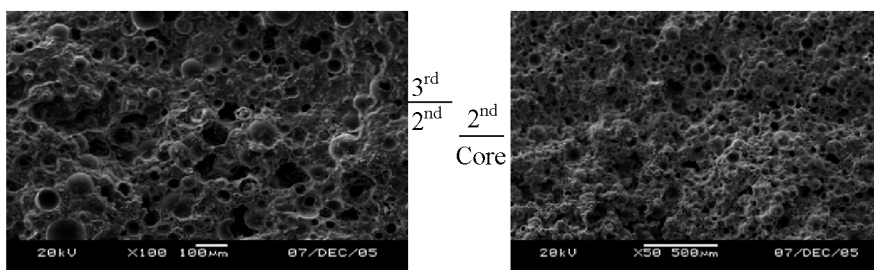


FIGURE 6. Interfaces between Layers of A 5-Layered Extrudate by SEM Using Secondary Electrons.

CONCLUSIONS

Using simple method of thin-walled tubes, layered feedrods of cementitious pastes were prepared and co-extruded to fabricate functionally graded cellular cement-based material. Inspections showed that the roundness perpendicular to the extrusion direction and the straightness parallel to the extrusion direction between layers were well preserved after extrusion and there was no debonding between layers.

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