Functionally graded concrete elements composed of vertical layers of different mixes

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Abstract

The industrial production of cement is currently responsible for 5-7% of global CO_2 emissions. The manufacture of functionally graded concrete structures, where the use of material is optimized by varying the material composition over the volume, opens up vast opportunities to reduce the use of cement. In functionally graded concrete, horizontal gradation can be achieved by casting vertical layers having homogeneous properties. However, a major problem with this kind of application is the control of the fresh state deformations. This study investigates the fresh state stability of concrete prisms that consist of two vertical layers of different mixes. Experiments are performed to invoke stable or unstable behaviour. The results show that, for a given geometry, a relationship between the material parameters and system stability exists.

Keywords: functionally graded concrete; tailored structures; fresh state; rheology; stability; vertical layers; optimization; plasticity.

1 Introduction

The industrial production of cement is currently responsible for 5-7% of global CO2 emissions. Hence, the development of technologies aimed at minimizing the use of cement in concrete structures, while preserving their strength and durability properties, plays a vital role in the reduction of carbon emissions.

Since the invention of concrete, structural elements have primarily been cast as homogenous continua having uniform properties. The traditional use of a single, homogeneous mix is reflected in current design codes and manufacturing methods. As a consequence, the realization of members with uniform concrete properties has become common practice in construction.

However, this approach typically only fully exploits the material properties in limited regions of a structural element. A material composition is selected in order to meet various requirements, such as a strength, durability and deformability performance. When, for example, the material is selected to achieve a certain strength performance, its full mechanical strength capacity is only required in regions where critical stress states develop. This often results in an overuse of high performance materials.

The use of material can be better optimized by manufacturing Functionally Graded Concrete (FGC) elements, i.e. tailored members where a spatial gradation in composition is designed for a specific function [1–5]. A spatial gradation in mix composition makes it possible to alter the material characteristics, including porosity, strength and rigidity over the volume of the element. This principle can be applied to minimize the use of cement by rationally employing concrete with high cement content only when it contributes significantly to the performance of the structure.

Concrete material properties can be graded in the vertical direction by casting horizontal layers of different mixes [1–5]. Yet relatively little attention has been paid to the possibility of grading the material composition in the horizontal direction, which represents a great opportunity to further optimize the use of cement in, for example, beams, columns and walls. An early experimental realization of vertically layered concrete members is reported in [6]. In such work, vertical layers of different mixes were cast with the aid of removable vertical panels that were extracted before setting.

However, a major problem with this kind of application is the control of the fresh state deformations of the vertical layers following a panel's removal (as shown schematically in Figure 1). Cementitious materials are yield stress fluids [7–9]. If the system is stable, there is limited flow and the column geometry is broadly maintained after the removal of the vertical panel. If the shear stresses are higher than the yield stress of the materials, flow occurs and the two materials may penetrate one another, therefore affecting the geometry the hardened state (see Figure 1).

This work contributes to research on functionally graded concrete by studying the mechanical stability of two vertical layers of different concrete mixes. Based on an original limit state analysis, a set of experiments on two vertical layers with tailored cementitious mixes is designed to invoke stable and unstable behaviour in the fresh state. The relationship between the material parameters, system stability and geometry is then determined and the formulated limit-state approach is validated against experimental results.

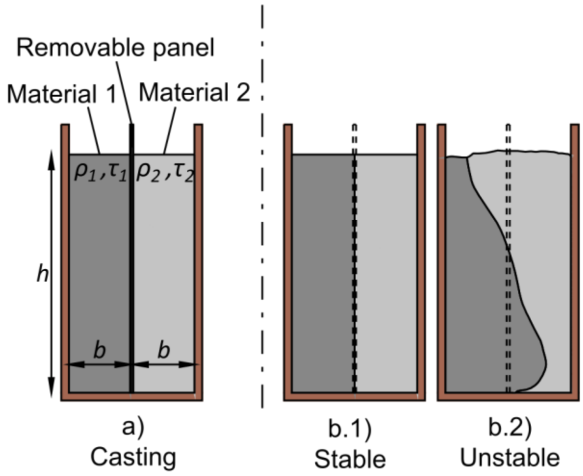

Figure 1 Stable and unstable fresh state behaviour of an element composed of two vertical layers of different mixes.

2 Limit state analysis

Fresh concrete is commonly modelled as a material that exhibits a viscoelastic solid behaviour for low shear stresses and flows at shear stresses higher than the yield stress. In this work it is assumed that either there is no flow or the flow is slow enough for viscous and inertia effects to be negligible [23]. This assumption allows the behaviour of fresh concrete to be studied as a function of the density and yield stress of the materials only [20,21]. Furthermore, the time-dependent changes in rheological properties are neglected and the yield stress is treated as a time-independent measure. This approach is valid when the characteristic flow time is shorter than the characteristic time over which the properties change [10]. In light of this, concrete in the fresh state is treated here as a perfectly plastic material.

The upper and lower bound methods of plasticity have been adopted to formulate two limit state models to assess the relationships between material properties, geometry, boundary conditions and stability of the system presented in Figure 1 [11]. For a given geometry and set of boundary conditions, the stability of the system can be controlled by varying the sum τ_s of the yield stresses of the materials and their difference in density $\Delta\rho$. Specifically, a plastic approach indicates that for a given geometry, fresh state deformations of the system decrease with increasing stability coefficient m, defined as:

$$m = \frac{\tau_s}{\Delta\rho} \quad (1)$$

In light of this, a set of experiments on two vertical layers with tailored cementitious mixes having various yield stresses and densities were designed to invoke stable and unstable behaviour.

3 Experimental design

To investigate the effects of yield stress and density on the stability of two columns of different materials, 12 tests were performed across 24 mix compositions. In each test, two identical layered concrete prisms composed of different pair of cementitious mixes were cast (see Figure 1). The mixes were mortars and the mix density was tailored through the addition of foam.

3.1 Materials

The mixes were designed in order to achieve sums of yield stresses ranging from 60 to 248 Pa and differences in densities of up to 375 kg/m^3 (see Table 1). Specifically, the yield stress was controlled by varying the water content from 230 kg/m^3 to 300 kg/m^3 and the superplasticizer content from 0 % to 1.05 % of cement mass (Table 2). The density was controlled by varying the content of foam from 0 l/m^3 to 200 l/m^3. The foam was produced in the laboratory prior to each test using a surfactant-based foaming agent. In order to distinguish the two materials employed in each test, a red mortar dye based on powdered oxide pigments was added to one of the mixes.

Table 1 Difference in weight Δρ, sum τ_s of the yield stresses, and stability coefficient m obtained for each test.

Measure	**T1**	**T2**	**T3**	**T4**
$\Delta\rho$ [kg m^{-3}]	330	368	350	375
τ_s [Pa]	192	151	104	67
m [Pa m³Kg-1]	0.58	0.41	0.30	0.18
Measure	**T5**	**T6**	**T7**	**T8**
$\Delta\rho$ [kg m^{-3}]	194	205	225	228
τ_s [Pa]	248	170	117	96
m [Pa m³Kg-1]	1.28	0.83	0.52	0.42
Measure	**T9**	**T10**	**T11**	**T12**
$\Delta\rho$ [kg m^{-3}]	208	142	125	75
τ_s [Pa]	60	157	144	61
m [Pa m³Kg-1]	0.29	1.10	1.15	0.82

Table 2 Mix composition ranges.
**Superplasticizer content in terms of % of cement mass*

Constituent	**Unit**	**Range**	
		Min	**Max**
Cement CEM I	[kg/m^3]	460	600
Water	[kg/m^3]	230	300
Sand 0/4 mm	[kg/m^3]	1100	1366
Superplasticizer*	[%]	0	1.05
Foam	[l/m^3]	0	200

3.2 Test sequence and methods

Each of the 12 tests involved mixing two different mortars, measuring their weight and rheological properties, and casting vertically layered prisms.

3.2.1 Mixing and rheological measurement

The two mortars were mixed simultaneously. The mixes without foam were mixed in a vertical-axis rotational mixer. By contrast, the foamed concretes were mixed in an inclined drum mixer. The yield stress of the wet mixes was measured through an LCPC-box test [12]. The wet density of each mix was measured at the same time. Measurements of the fresh state properties and stability tests were performed and completed within 10 minutes after mixing.

3.2.2 Main experiments

For each test, two identical specimens (named *A* and *B*) were cast. Rectangular wooden moulds with internal dimensions of 16.4 × 30 × 35 cm^3 were equipped with a removable vertical panel (see Figure 2). The vertical panel was made of acrylic glass and was 4 mm thick, therefore dividing the internal volume of the mould into two distinct regions having a thickness of 8 cm.

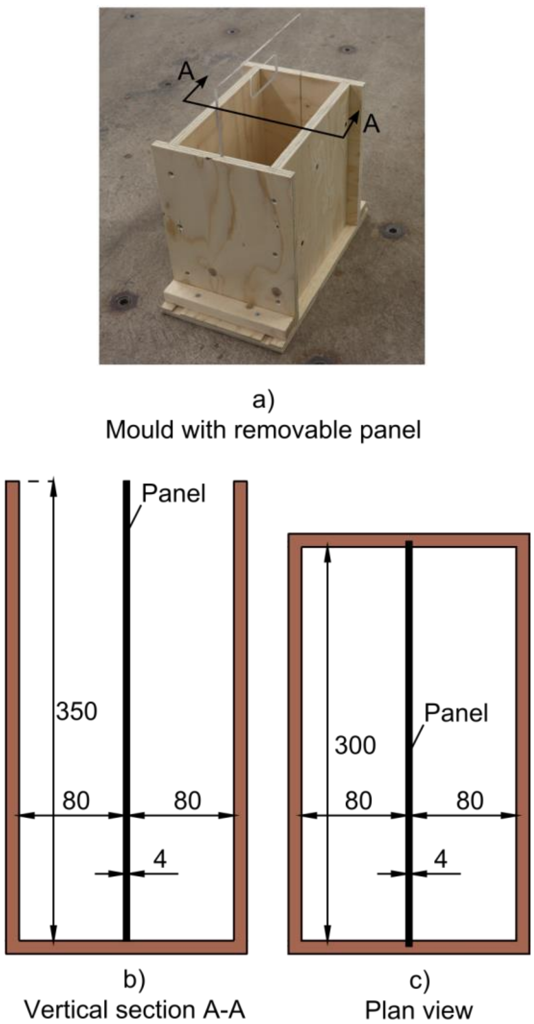

Figure 2 Moulds with panel. Dimensions in mm.

First, the removable panel was oiled to minimize the friction effects on sliding. Then, two different mixes were simultaneously cast in the two regions of the mould. The two regions of the mould were filled up to a height of 30 cm. The dividing panel was then removed immediately after casting. To avoid inducing inertial effects, the panel was extracted in approximately 10 seconds, corresponding to a relatively low speed of 30 mm s^{-1}. The two columns of material deformed to fill the gap created by the panel extraction and came into contact.

The specimens were cured for at least 3 days, demoulded, and cut in half along the vertical plan parallel to their short sides. This allowed the middle cross section of the specimens to be inspected (see Figure 3a). The cross sections were photographed with a high-resolution camera (Figure 3b). The perspective distortions were minimized upstream by ensuring the focal plane was parallel to the cuts and the residual distortions were corrected in a raster graphic editor. A CAD software was used in order to trace the profile of the boundary between the two mixes and to measure the transversal displacement *d*, defined here as the maximum horizontal displacement d of the boundary (see Figure 3c).

4 Results

In all the tests, the heavier material tends to flow underneath the lighter material, as postulated in the mechanism analyses. The short lateral faces of all specimens did not deform. In other words, the fresh materials stuck to the walls of the moulds. Nevertheless, the inspection of the boundary between the two materials at the top surface of the prisms showed that the short lateral faces affected only a limited region of the specimens over a maximum thickness of 9 cm toward the middle section of the specimens.

Figure 4 shows the maximum displacements d_A and d_B obtained for repeat tests *A* and *B* respectively plotted against the corresponding stability coefficient m.

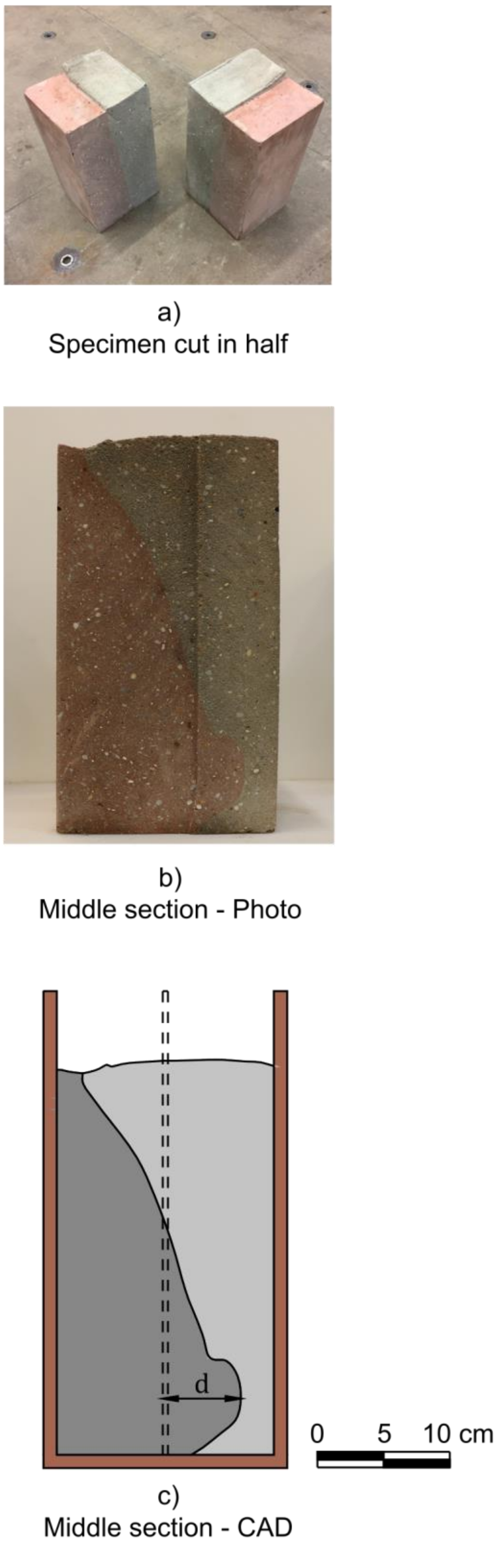

Figure 3 Analysis of the middle section of a specimen

The plot suggests that, according to the formulated bound models, a relationship exists between the difference in density $\Delta\rho$ of the two materials, the sum of their yield stresses τ_s, and the stability of the system. The displacements decrease with the stability coefficient m. Specifically d decreases sharply for stability coefficients m up to about 0.4 Pa m³ kg^{-1} and more gradually for higher values of m.

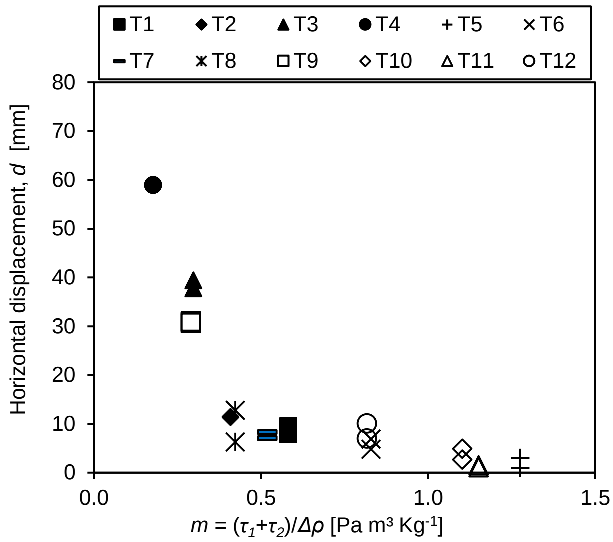

Figure 4 Horizontal displacement d as a function of the stability coefficient m.

5 Discussion

The experimental results suggest that, for a given system geometry, the stability of the system in the fresh state can be controlled by tailoring the material properties of the two mixes. The sum of the yield stresses τ_s and difference in density $\Delta\rho$ between the two mixes drive the fresh state behaviour of the two columns (see Figure 4). The difference in density $\Delta\rho$ affects the initial stress state after panel removal while the sum of yield stresses τ_s is an effective indicator of the fresh state strength of the system. Accordingly, the stability capacity of the system can be expressed through a stability coefficient m, defined here as the ratio between the sum of the yield stresses τ_s and the difference in densities $\Delta\rho$.

When layered elements composed of vertical columns of different mixes are cast with the aid of removable panels, the two materials come into contact. An explanation of the underlying mechanisms may be obtained by thinking of cementitious materials as yield stress fluids [7,9]. The extraction of the panel creates a void that causes high shear stresses in the two materials. Therefore, flow occurs and the materials fill the void. Once the void is filled, two situations may occur. If the difference in density between the two materials is small, the mutual confinement of the two columns leads to stress states that do not exceed the yield stresses of the materials. Thus, the material does not flow. If on the other hand the difference in density is high enough to cause shear stresses greater than the shear stress of the materials, the material starts to flow. The flow stops when the deformed shape of the system corresponds to a stress state that does not exceed the yield stress of the materials.

Cementitious materials exhibit visco-elastic behaviour for low shear stresses [7,9]. Thus, the distortions observed in the hardened specimens are expected to include the macroscopic effects of elastic and creep strains. The development of visco-elastic strains, together with potential imperfections of the moulds, might explain the relatively small distortions measured for high values of the stability coefficient m.

For the mortars considered in the current work the transition regime between stable and unstable conditions is represented by stability coefficients of about 0.4 Pa m^3 kg^{-1} (see Figure 4).

6 Conclusions

The design and manufacture of functionally graded concrete structures allows for a reduction of the use of cement at a global scale. This work contributes to research on functionally graded concrete by studying the fundamental problem of fresh state stability of two vertical layers of different mortar mixes.

The following conclusions can be drawn:

- For a given geometry and set of boundary conditions, the transition between stable and unstable regimes is expected to occur when either the difference in density $\Delta\rho$ is increased or when the sum τ_s of the yield stresses is decreased.
- Such a trend is confirmed experimentally. Specifically, it was shown that for a given geometry, fresh state deformations of the system decrease with increasing stability coefficient m, defined here as the ratio between the sum τ_s of the yield stresses and the difference in density $\Delta\rho$.

7 Acknowledgements

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8 References

[1] Toader N, Sobek W, Nickel KG. Energy absorption in functionally graded concrete bioinspired by sea urchin spines. J Bionic Eng 2017;14:369–78. doi:10.1016/S1672-6529(16)60405-5.

[2] Herrmann M, Sobek W. Functionally graded concrete: Numerical design methods and experimental tests of mass-optimized structural components. Struct Concr 2016;18:54–66. doi:10.1002/suco.201600011.

[3] Roesler J, Paulino G, Gaedicke C, Bordelon A, Park K. Fracture behavior of functionally graded concrete materials for rigid pavements. Transp Res Rec J Transp Res Board 2007;2037:40–9.

[4] Evangelista F, Roesler J, Paulino G. Numerical simulations of fracture resistance of functionally graded concrete materials. J Transp Res Board 2009:122–31.

[5] Zhang J, Li VC. Monotonic and fatigue performance in bending of fiber-reinforced engineered cementitious composite in overlay system. Cem Concr Res 2002;32:415–23. doi:10.1016/S0008-8846(01)00695-0.

[6] Heinz P, Herrmann M, Sobek W. Production method and application of functionally graded components in construction (Herstellungsverfahren und Anwendungsbereiche für funktional

gradierte Bauteile im Bauwesen). Stuttgart: Fraunhofer IRB Verlag; 2012.

[7] Coussot P. Yield stress fluid flows: A review of experimental data. J Nonnewton Fluid Mech 2014;211:31–49. doi:10.1016/j.jnnfm.2014.05.006.

[8] Tattersall GH, Banfill PFG. The rheology of fresh concrete. Boston: Pitman Books Limited; 1983.

[9] Banfill PFG. Rheology of fresh cement and concrete. Rheol. Rev. 2006, The British Society of Rheology; 2006, p. 61–130.

[10] Coussot P. Saffman–Taylor instability in yield-stress fluids. J Fluid Mech 1999;380:S002211209800370X. doi:10.1017/S002211209800370X.

[11] Torelli G, Lees JM. Fresh state stability of vertical layers of concrete. Under Rev 2018.

[12] Roussel N. The LCPC BOX: a cheap and simple technique for yield stress measurements of SCC. Mater Struct 2007;40:889–96. doi:10.1617/s11527-007-9230-4.