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Functionally graded concrete: Design objectives, production techniques and analysis methods for layered and continuously graded elements

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Abstract

The pressing need to reduce global carbon emissions together with recent advances in automated manufacturing have driven a growing interest in functionally graded concrete. In functionally graded concrete, the material composition is spatially varied to meet performance demands that differ within regions of a structural element. This offers significant potential to reduce cement consumption. Step-wise layered and continuously graded concrete systems are introduced and investigations of concrete mix combinations to achieve durability, fracture resistance, strength, ductility, cost saving, weight reduction or lower embodied energy improvements are discussed. Production techniques for horizontally layered and vertically layered structural elements in the context of fresh-on-hardened and fresh-on-fresh casting as well as emerging continuously graded processes are presented. Challenges associated with fresh-state deformations, layer interfaces and the need for appropriate fresh and hardened-state modelling tools are critically assessed.

Keywords

Concrete; Functionally graded concrete; Functional gradation; Layered concrete; Tailored concrete.

1 Introduction

Concrete is the most widely used material in construction. Consumption of cement, the key ingredient of concrete, is responsible for about 5% of the global CO_2 emissions associated with human activities [1]. Concrete structural elements are traditionally cast using a single, homogeneous mix. The ubiquitous use of concrete as a homogeneous material is reflected in current design codes and manufacturing methods. To meet requirements such as a strength, durability and deformability, a suitable set of material properties are specified. An appropriate concrete mix composition is then selected. Consequently, the material properties in a homogeneous member are generally underutilised in most locations. When, for example, a relatively low water to cement ratio is selected to meet a durability requirement, the resulting low permeability material is only fully exploited in peripheral regions where water and gas diffusion present a threat to durability.

The use of concrete can therefore be optimized through functional grading. In functionally graded materials, the mix composition is varied over the geometry of an element to tailor the material properties to local needs. This allows multiple requirements to be met by rationally employing a given material composition only when it significantly contributes to one or multiple functions of the element. Functional gradation of concrete offers two main opportunities to achieve cement reduction:

- Using cement efficiently by employing concrete mixes with high cement content only where it is strictly needed to achieve a given performance measure, such as strength or durability. This can be achieved, for example, by locally reducing cement content or using alternative binders.
- Minimizing the overall weight of concrete structures by employing lightweight mixes where normal weight mixes are not needed. In this way, dead loads are minimized. Consequently, more slender structural elements can be designed that use less material.

The concept of engineered functionally graded materials draws inspiration from nature. Numerous biological systems such as plant stems and animal bones have evolved ingeniously by developing spatially graded composition, microstructure and properties to respond to a variety of external stimuli [2–5]. For example, bamboo has developed a self-sensing system that drives the growth of a graded microstructure to produce spatially varying mechanical properties [2–4] – see Figure 1. The concept of functional grading has been applied extensively to solve engineering problems in the fields of energy, aerospace and bioengineering [6–8]. Functionally graded components that combine the thermal insulation properties of ceramics with the mechanical performance of metals [9–11] are widespread and employed extensively in thermal barrier coatings in pressure vessels and to withstand high thermal gradients in space applications. Functionally graded prostheses mimic a natural gradation in mechanical properties to replace damaged human body tissues. Detailed reviews on the history, processing techniques and applications of functionally graded materials are presented in [8,12–16].

Figure 1 Cross section of bamboo culm showing a non-uniform distribution of fibres through the thickness.

Although functional grading has been successfully implemented in several industries, it has traditionally received little attention in concrete construction. This can be attributed to: the relatively low cost of concrete, which has led to a widespread culture of overdesign of concrete structures, and the lack of production processes to efficiently realise Functionally Graded Concrete (FGC) elements. Current sustainability priorities for lifetime extension, energy minimisation and a reduction in over-engineering means that graded concrete offers a significant opportunity to optimize the use of cement and concrete. Furthermore, recent advancements in robotics have unveiled the potential to automate the manufacturing of FGC elements to facilitate more efficient and controlled production of tailored components.

A comprehensive survey of the state-of-the-art of envisioned performance enhancements, structural applications, production processes and design and analysis methods for FGC is undertaken. Aspects of both the fresh-state and the hardened-state structural behaviour are explored to provide extensive insight into the interplay between competing objectives.

2 Design concepts and applications

In this paper, non-homogeneous concrete compositions are classified into two main categories based on the desired topology: layered or continuously graded concrete. *Layered concrete* is defined here as concrete material with a step-wise spatial variation in composition, i.e. a variable-composition material composed of layers having homogeneous properties (see Figure 2a). *Continuously graded concrete* refers to concrete with a continuously variable composition (see Figure 2b).

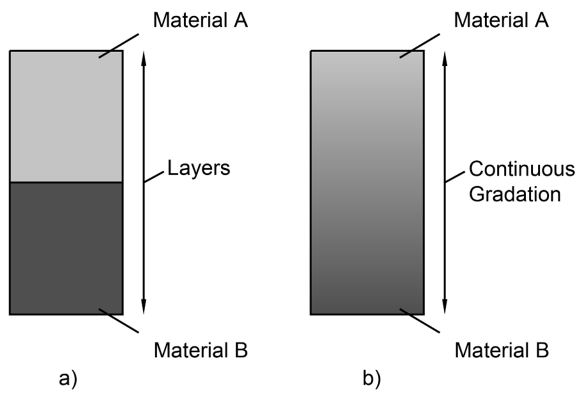

Figure 2 Schematic illustration of (a) layered concrete and (b) continuously graded concrete.

A spatial variation of material composition can optimize elemental properties to meet certain design requirements. To date, cement reduction, weight minimisation, improved post-fracture behaviour and an enhanced durability of concrete elements have been key drivers. In the following, the design objectives explored in existing studies about layered and continuously graded concrete are reviewed and the potential enhancements from functional grading are assessed.

2.1 Layered concrete

Much of the research on functional advantages of layered concrete has been conducted on two-layer horizontally cast prismatic elements, with or without longitudinal steel reinforcement. For purposes of comparison, the geometric parameters will be defined here as the specimen width *b*, overall height, *h*, length *l*, concrete cover *c* and thickness of the lower layer *t* (see Figure 3). An overview of typical unreinforced and reinforced specimen sizes, mix combinations and design objectives can be found in Table 1.

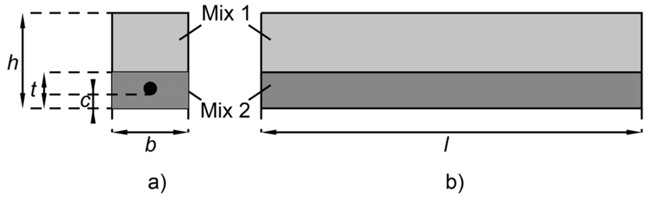

Figure 3 Typical geometry of a two layer horizontally cast prismatic element: (a) cross section and (b) lateral view.

Table 1 Two layer horizontally cast prismatic elements subjected to bending loads: pilot experiences. Concrete mixes without reinforcing fibres or alternative binders are referred to as *Normal Concrete*.

Year	Ref.	Longitudinal Steel reinforcement	Element dimensions [mm]	Bottom layer material	Top layer material	Time between pours	Design concept	Enhancement Measure [%]
1995	[17]	Yes	b = 102 h = 152 l = 914 c = 12 t = 51	Engineered Cementitious Composite (ECC)	Normal Concrete	60 min	Improved durability	Up to 80% reduction in crack width.
2003	[18]	Yes	b = 210 h = 240 l = 2500 c = 45 t > 45	Ductile Fiber-Reinforced Cementitious Composite (DFRCC)	Normal Concrete	60 min	Improved durability	About 70% increase in time needed to achieve a given level of steel loss.
2007	[19]	No	b = 80 h = 150 l = 700 t = 100	Normal Concrete / Fiber Reinforced Concrete (FRC)	Normal Concrete / Fiber Reinforced Concrete (FRC)	0 min	Improved fracture behaviour	Up to 108% increase in relative fracture energy (calculated at 2-mm opening displacement)
2009	[20]	Yes	b = 80 h = 120 l = 2000 c = 28 t = 15 / 20 / 25 / 35 / 50	Ultra-High Toughness Cementitious Composite (UHTCC)	Normal Concrete	60 min	Improved durability, load capacity and ductility.	About 80% reduction in crack width, 30% increase in load bearing capacity, and

								70% increase in deformation ability.
2013	[21]	No	*b* = 100 *h* = 150 *l* = 600 *t* = 0 / 25 / 50 / 75	High Volume Fly-Ash Concrete (HVFAC)	Normal Concrete	n.a.	Cost minimization, Improved durability and strength	About 10% reduction in cement content, about 3% increase in load bearing capacity.
2014	[22]	No	*b* = 300 *h* = 100 *l* = 1350 *t* = 50	Polypropylene fibres reinforced concrete / Steel fiber reinforced concrete	Polypropylene fibres reinforced concrete / Steel fiber reinforced concrete	n.a.	Cost minimization, Improved strength	Up to about 480% increase in fracture toughness
2016	[23]	Yes	*b* = 150 *h* = 250 *l* = 3000 *c* = 15 *t* = 200	Fibre-Reinforced Lightweight Concrete (FRLWC).	Normal concrete	1 week	Weight reduction	About 42% reduction in weight.
2018	[24]	No	*b* = 150 *h* = 150 *l* = 500 *t* = 75	Normal Concrete / FRC / Recycled Aggregate Concrete (RAC)	FRC/ Recycled Aggregate Concrete (RAC)	20 min	Embodied energy and cost minimization	About 48% reduction in embodied carbon, about 43% reduction in cost, about 21% reduction in strength.

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Investigations into layered concrete beams have demonstrated that performance enhancements such as cement or weight reduction can be achieved through judicious selection of mix combinations. Bajaj et al. [21] designed two-layered unreinforced concrete beams having a top layer of normal concrete and a bottom layer of High Volume Fly-Ash Concrete (HVFHC). Their results showed that employing HVFHC with replacement of 35% of cement with fly ash in the area subject to tensile stresses allows the use of cement to be substantially minimized while preserving strength and durability properties. Nes and Øverli [23] realized two-layered reinforced cross sections with a bottom layer of low-density fibre-reinforced concrete and a top layer of normal density concrete. Their results showed that a self-weight reduction of 42% can be achieved compared to a homogenous cross section of normal concrete with a comparable bending capacity.

The fracture behaviour of unreinforced concrete can also be modified though functional grading. Roesler et al. [19] studied the fracture of homogeneous normal concrete and fiber-reinforced concrete (FRC) beams subjected to bending, and compared these to layered beams combining normal and fiber-reinforced concrete (see Figure 4). A notch of depth equal to one-third of the specimen height was cut into the bottom surface of each specimen prior to testing. Figure 5 shows the applied load against Crack Mouth Opening Displacement (CMOD) results. The curves indicate that all the concrete specimens exhibited similar elastic behaviour and peak stresses. However, the specimens with fibre reinforcement showed an improved residual strength and ultimate displacement. The homogeneous FRC beam exhibited the highest residual strength but a comparison of the layered beams shows that fibre-reinforced concrete is more effective when used for the bottom layer of the beam. This is because failure occurs due to concrete cracking at the crack tip. Thus, if the post-peak behaviour of unreinforced concrete elements is to be optimized, a bottom layer of FRC is advantageous.

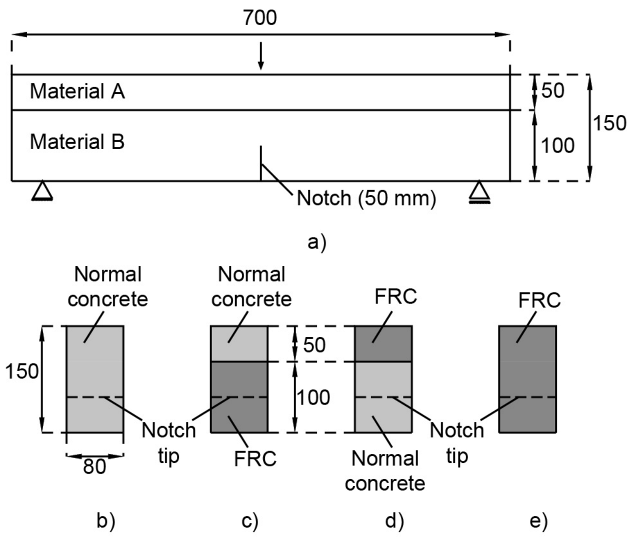

Figure 4 Functionally layered beams realized by Roesler et al. [19]: a) geometry, load and boundary conditions, and cross sections of b) a homogeneous beam of normal concrete, c) a layered beam with normal concrete at the top and Fibre-Reinforced-Concrete (FRC) at the bottom, d) a layered beam with FRC at the top and normal concrete at the bottom, and e) a homogeneous beam of FRC. Adapted from Roesler et al. [19].

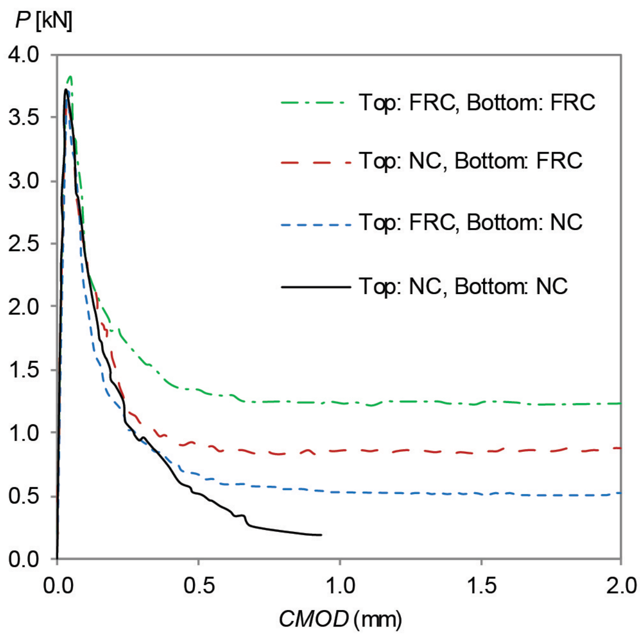

Figure 5 Average load-CMOD envelope curves for the cross sections (b), (c), (d), and (e) presented in Figure 4. Adapted from Roesler et al. [19].

Functional concrete gradation can be adopted to improve the durability properties of reinforced concrete structures. A major durability issue in reinforced concrete is corrosion of the internal steel reinforcement [25]. The main causes of reinforcement corrosion are concrete carbonation, due to CO_2 ingress, and penetration of aggressive substances, such as chlorides or acidic gases [25,26]. Initially, the concrete cover acts as a physical barrier against the penetration of aggressive materials. In the long term, however, deleterious materials penetrate through pores and cracks. When they reach the reinforcement, they depassivate the steel reinforcement and corrosion starts to develop. From a concrete perspective, the penetration of aggressive substances can be delayed by minimizing the concrete permeability, extent of cracking and crack widths [25,27]. Since aggressive substances initially penetrate through the concrete cover, these desirable durability properties are primarily required in the peripheral regions of a structural element exposed to chemical attack.

Wen et al. investigated the possibility of protecting steel reinforcement through an external layer of low-permeability concrete [28]. Specifically, they experimentally characterized the relationship between the thickness of the protective layer and the resulting corrosion-protection. Low-permeability concrete was obtained by using water repellents, aimed at reducing the capillary fluid transfer, and by adding PVA fibres to guarantee strain-hardening and multiple-cracks in tension. Rapid chloride penetration tests and accelerated steel bar corrosion tests were performed on unloaded reinforced concrete specimens with protective layers of various thicknesses (Figure 6). Figure 7 shows the measured chloride content of specimens at 210 days in an accelerated environment. These results show that an optimum thickness exists for the protective layer. Significant durability protection is achieved with a 10-mm-thick protective layer, while no major gains in protection are obtained by further increasing the layer thickness. Worth noting is that if the thickness is increased such that the interface between the two materials is aligned with the steel bars, a slightly higher degree of corrosion develops. This unexpected result was attributed to differences in electrochemical properties and permeability between the two materials. However, further research is required to fully understand the underlying mechanisms.

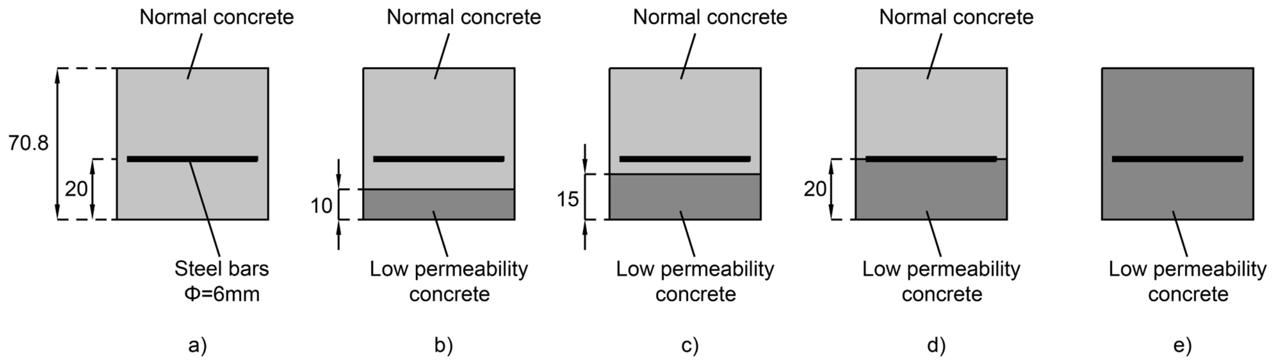

Figure 6 Reinforced concrete specimens with protective low-permeability layer realized by Wen et al. [28]: (a) homogeneous normal-concrete, (b) 10-mm-thick protective layer, (c) 15-mm-thick protective layer, (d) 20-mm-thick protective layer, and (e) homogenous low-permeability concrete. Adapted from Wen et al. [28].

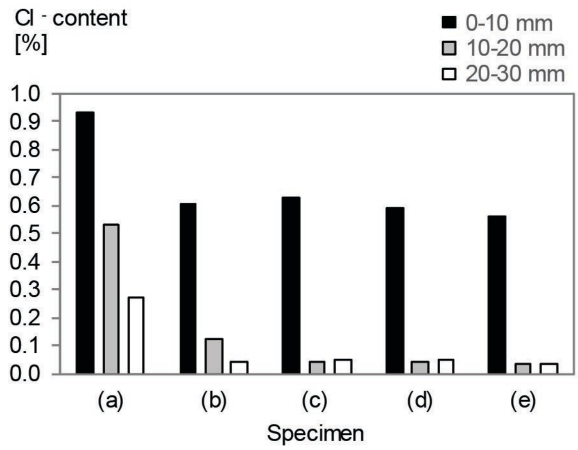

Figure 7 Cl^- content at different depths (0-10 mm, 10-20 mm, and 20-30 mm) for the specimens (a), (b), (c), (d) and (e) presented in Figure 6. Adapted from Wen et al. [28].

Reinforced concrete beams with layers of strain-hardening composites in peripheral tensile areas have also been designed to limit crack widths under service flexural loads to improve durability. Maalej and Li designed two-layered reinforced concrete beams with a bottom layer of strain-hardening Engineered Cementituous Composite (ECC) and a top layer of normal concrete [17]. For a given load level, the introduction of an ECC layer allowed crack-width reductions of up to about 80%. These results show that crack widths under service flexural loads can be effectively limited by introducing an ECC layer in the area subjected to tension. Hence, the introduction of a material with multiple-cracking behaviour in layered beams delays and limits the ingress of aggressive substances. In addition, when concrete surrounding longitudinal bars is replaced with strain-hardening material, any cracks induced because of steel corrosion are likely to be limited in width, or arrested before reaching the exposed surface. Similar reductions in crack width can be achieved by substituting the concrete surrounding longitudinal bars with Ductile Fiber Reinforced Cementitious Composite (DFRCC) material [18]. In 2009, Li and Xu [20] investigated the flexural behaviour of two-layered beams with a bottom layer of Ultra-High Toughness Cementitious Composite (UHTCC) and a top layer of normal concrete. Beams with different thicknesses of UHTCC layer were tested. Their results showed that UHTCC can also be adopted as an effective replacement of concrete to control the crack width. Furthermore, the introduction of a UHTCC led to an improved load bearing capacity and ductility compared with homogeneous beams of normal concrete. Specimens with a 35-mm-thick UHTCC layer (see Figure 8c) exhibited crack widths below 0.5 mm at yield, a 30% higher load bearing capacity and a 70% greater deformation ability than control homogeneous elements of normal concrete. No significant gains in crack-width control, strength and ductility were measured for beams with a thicker UHTCC layer. Thus, the thickness of the UHTCC layer which extends to just above the steel reinforcement (see Figure 8c) was found to be the optimal thickness.

These results indicate that the use of low-permeability and multiple-cracking behaviour mixes in the exposed surface regions of reinforced concrete allow the penetration of aggressive substances to be delayed, thereby boosting the durability of structural members. What remains unclear, however, is whether interfaces between concrete layers might offer preferential paths for aggressive substances. Further research is therefore required to examine the effects of production processes and mix design parameters on the mass transport and microstructure of concrete at interfaces between layers.

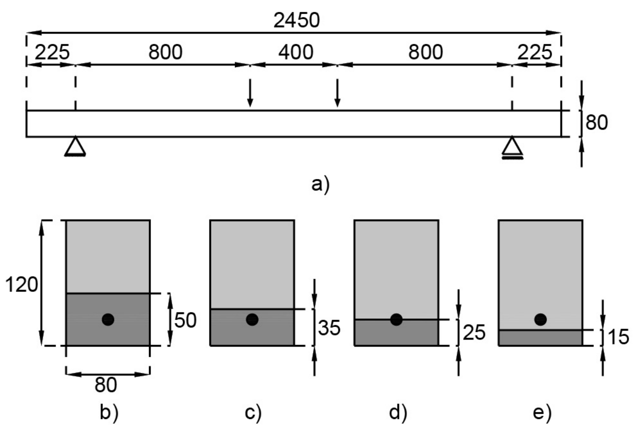

Figure 8 Functionally layered beams realized by Li and Xu [20]: a) geometry, load and boundary conditions, and cross sections for a bottom UHTCC layer having a thickness of b) 50 mm, c) 35 mm, d) 25 mm and e) 15 mm. Adapted from Li and Xu [20].

Han et al. [29] explored the mechanical behaviour of unreinforced concrete cylinders composed of two layers of different materials subjected to axial loading (see Figure 9). Their results showed that when two mixes with different stiffnesses and compressive strengths are used, the strength of the composite cylinders approximately equals the strength of the weakest material. By contrast, the stiffness of a composite cylinder lies between the stiffness of the two individual mixes.

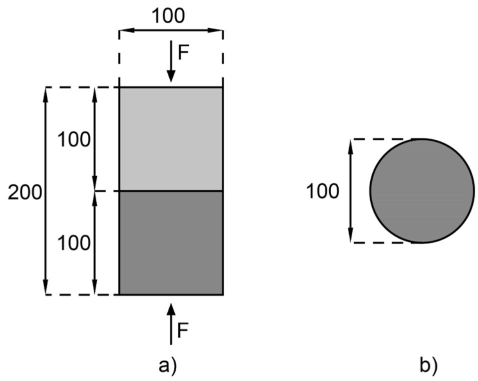

Figure 9 Unreinforced concrete cylinders composed of two layers of different mixes: (a) lateral view and (b) cross section. Adapted from [29].

Heinz et al. [30] explored the possibility of realising reinforced concrete elements composed of multiple horizontal and vertical layers of different mixes, to minimize both the cement content and self-weight of concrete beams subjected to shear and bending. Concrete mixes characterized by relatively high porosity, and poor mechanical properties, were employed in the regions of the element where relatively low stresses were expected in order to minimize the element mass (see Figure 10). The density of the materials was controlled by varying the porosity of the cement paste, through the addition of foam that further allowed cement content minimization, and the aggregate type, using lightweight aggregates for self-weight reduction.

The results obtained showed that the layered beam reached the calculated flexural and shear resistance values with a mass reduction of 34% compared to a homogenous beam.

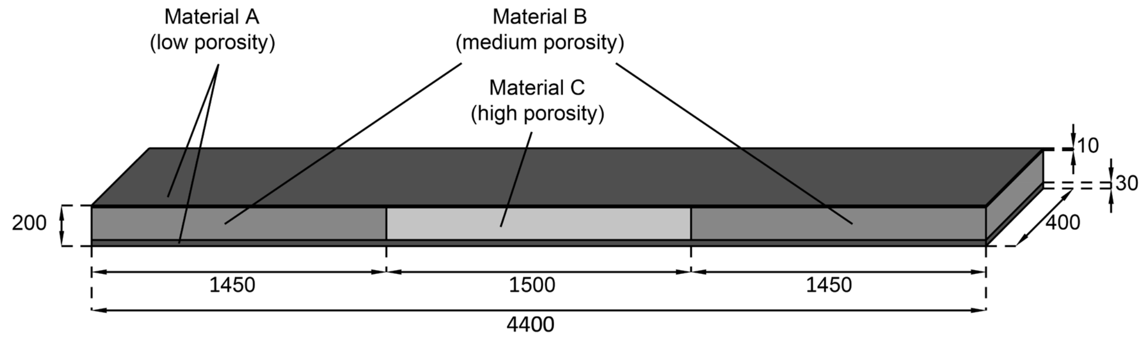

Figure 10 Multi-layer beam realized by Heinz et al. [30]. Adapted from [30].

2.2 Continuously graded concrete

In recent years, a number of authors have investigated the advantages of continuously graded concrete. In 2011, Oxman et al. [31] explored the concept of grading the density to minimize self-weight and cement content in unreinforced concrete cylinders subjected to bending. Through theoretical calculations, they showed that cylinders with a radial density gradient can be produced having 9% less mass than a solid cylindrical beam having the same dimensions and bending capacity. This is achieved by varying the material density in the radial direction and setting the tensile strength f_t at the external surface of the cylinder equal to the expected tensile stress (see Figure 11). Herrmann and Sobek [32] designed a 4-m span beam with continuously graded porosity to minimize weight. The optimum spatial variation in porosity was determined through a numerical optimization procedure based on iterative finite element analyses. The results of the numerical study suggest that the continuously graded concrete beam allows a weight reduction of up to 62% to be achieved compared to a homogeneous structural component. Through numerical analyses, Craveiro et al. [33] demonstrated that weight savings of up to 27%, together with an improved thermal performance, can be achieved by designing structural walls with a continuously varying concrete composition. Their results were obtained by assuming a spatially varying content of lightweight aggregates. More recently, Kovaleva et al. [34] applied the concept of continuous porosity gradation to minimise the weight of concrete shells. Specifically, they designed a continuously graded concrete shell whose optimum porosity distribution was determined through an integrated computational design environment. As a result, the weight of the structure was reduced by 40% without decreasing its numerically estimated load-bearing capacity.

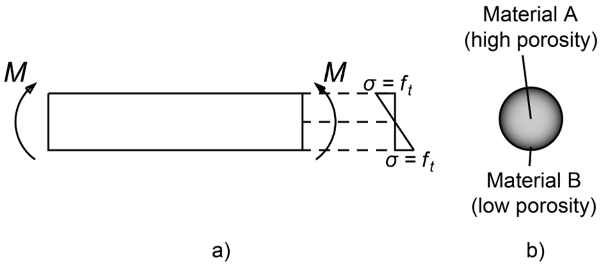

Figure 11 Cylinder with a radial density gradient designed by Oxman et al. [31]: (a) normal stress distribution for a bending moment causing cracking at the external surface of the cylinder and (b) graded material porosity in the radial direction.

Strieder et al. [35] studied the possibility of employing continuously-graded concrete to minimize cracking associated with hydration heat in mass concrete, thereby improving durability. Hydration heat can be limited through using concrete mixes with low cement content. However, these mixes are not suitable for the concrete cover to reinforcement, where a high cement content is generally required to achieve low permeability and reduce penetration of aggressive substances. Through a series of illustrative FE analyses, the authors showed that the hydration heat developing on hardening can be significantly reduced through functional gradation of cement content. By using mixes with high cement content only in the concrete cover (see Figure 12), the overall hydration energy can be significantly reduced. Thus, cracking induced by thermal gradients is minimized and the durability properties of the element are improved.

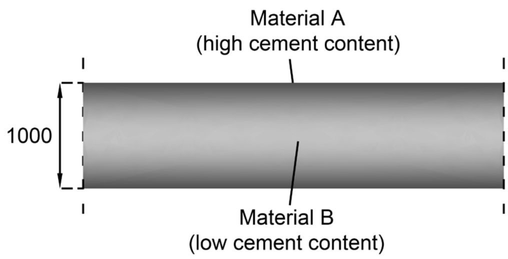

Figure 12 Mass concrete element with a functional gradation of cement content designed by Strieder et al. [35]. Adapted from Strieder et al. [35].

Although promising, existing analytical and numerical research on continuously graded concrete needs to be supported by experimental evidence. Furthermore, the inherent limitations of current technologies for the production of continuously graded concrete need to be overcome to translate the discussed design concepts into practice.

3 Production methods

This section describes, classifies and critically discusses available methods of manufacturing concrete elements with spatially varying material composition. Techniques for casting elements with non-homogeneous concrete composition are classified using the topology-based categories introduced previously, namely layered or continuously graded concrete casting techniques.

3.1 Layered concrete

Layered concrete elements can be divided into two main groups according to the sequence of casting operations: fresh-on-hardened and fresh-on-fresh casting methods. In fresh-on-hardened casting, new layers of fresh concrete are added only when previous layers have set and hardened. By contrast, in fresh-on-fresh casting different concretes are mixed and cast simultaneously. The different concrete mixes in the layered elements therefore set and harden at approximately the same time.

3.1.1 Fresh-on-hardened casting

Fresh-on-hardened casting is common in the precast industry, where *in-situ* concrete is poured on top or within a precast section to obtain composite beams or floors [36]. Functional layering is commonly employed to improve the mechanical properties of structural members in areas subjected to significant mechanical stresses or aggressive environments. Examples of fresh-on-hardened casting include the application of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) concrete layers to boost the strength and durability performance of bridge decks [37,38] (see Figure 13). Fresh-on-hardened casting procedures are also frequently employed to achieve functional gradation for the realization of structural connections between precast elements (see Figure 14). When concrete is poured in-situ to connect precast elements, high-strength low-permeability mixes are generally adopted to meet the local strength, deformability and durability requirements [39]. The widespread use of fresh-on-hardened techniques in construction is reflected in a number of codified methods to evaluate the bond strength capacity of the interfaces between layers, usually referred to as cold joints [40–48].

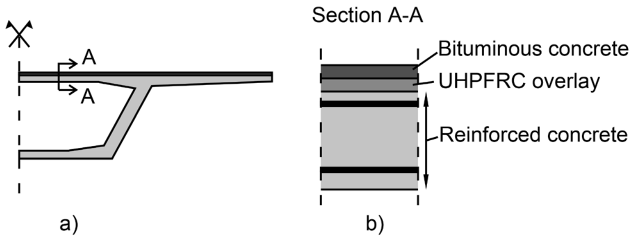

Figure 13 Schematic representation of a typical composite bridge cross-section cast fresh-on-hardened: (a) cross section of the bridge and (b) section A-A of the bridge deck. Adapted from [38].

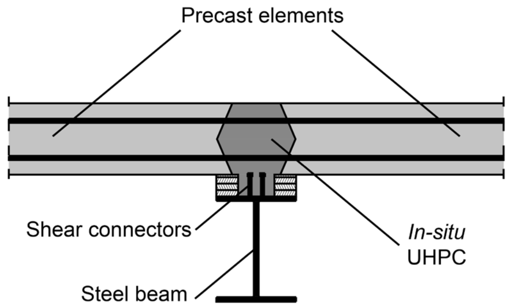

Figure 14 Schematic representation of a typical connection of two precast bridge-deck elements. Adapted from [39].

A major advantage of fresh-on-hardened over fresh-on-fresh casting is that it allows the geometry of the layers and the location of each interface to be accurately monitored during production, since new layers are added only when the existing ones have hardened. Another practical advantage is that it does not complicate the logistics by requiring multiple concrete mixes to be mixed at the same time. Instead, a single concrete mixer can potentially be employed to manufacture layered elements composed of an arbitrary number of mixes. However, casting new layers only when the existing ones have hardened presents a disadvantage in terms of production speed and may therefore limit adoption of layered element manufacture in precast construction plants.

Another limitation of fresh-on-hardened casting is that transverse steel reinforcement is generally required to guarantee a good bond between layers and ensure full composite action. If new layers are added *in situ*, the effectiveness of the concrete-to-concrete adhesion strongly depends on the workmanship and cleanliness of the older hardened concrete surface when the fresher mix is poured. Due to the variability in the quality control on construction sites, it is generally assumed that adhesion is limited. A further limiting factor is differential drying shrinkage, which is the time dependent contraction caused by the drying out of concrete. Drying shrinkage strains can reach values of up to 4×10^{-3}, with the bulk developing within the first few months of drying [49]. Hence, in practical applications involving relatively long times between castings, progressive drying of the new mix can lead to early age shrinkage contractions that are restrained by the older concrete. This might result in tensile stresses and tension-induced cracking in the new concrete in the proximity of the interface.

3.1.2 Fresh-on-fresh casting

Although still in early stages of development, fresh-on-fresh casting techniques for layered concrete are being developed. Horizontal layering has similarities with conventional casting processes with the exception that multiple mixes are used which introduces additional fresh and hardened-state compatibility constraints. Vertical layering is promising but is more challenging to achieve and the production approaches are in the realms of fundamental research. Both horizontal and vertical layering are subsequently discussed.

Horizontal layers

In the fresh state, concrete is a yield stress fluid, that is, a material that exhibits solid behaviour for low shear stresses and starts to flow when a threshold shear stress is exceeded [50–52]. This threshold shear stress, referred to as yield stress, is generally small enough for the material to flow under its own weight and fill a mould [53]. The exploitation of this property has encouraged a number of researchers to manufacture layered concrete elements by sequentially casting horizontal layers of different materials. The material yield stress is a time and process dependent parameter. It will increase as the material sets and reduce with vibration. Factors including the time between the casting of each layer, rheology, mix compatibility, vibration process, deposition method and casting sequence will dictate both the stability of the layered system in the wet state and the resulting hardened state performance.

A potential practical advantage of using fresh-on-fresh casting is the potential for significant reduction in manufacturing time. Furthermore, an additional advantage of this casting method is the possibility to achieve a good bond between layers without relying on transversal reinforcement. Perfect adhesion could theoretically be achieved by casting the layers sequentially in controlled conditions, provided that compatible mixes are selected. As with fresh-on-hardened casting, the efficiency of well executed fresh-on-fresh joints may be compromised by the appearance of cracks due to strain incompatibilities between the two mixes. However, in the case of fresh-on-fresh casting, more limited constraining effects are generally provided by older layers still in the fresh state. Strain incompatibilities are therefore expected to arise due to drying and shrinkage differentials between the two mixes.

However, a major challenge in the adoption of fresh-on-fresh casting is the control of the potential local concrete flow at the interface between the materials in the fresh state. Indeed, excessive flow can result in a spatial distribution of material composition that significantly differs from that targeted in the design. Local flow can occur when, for example, a heavier mix is poured on top of a lighter mix, and the mixes are not stiff enough to withstand the resulting shear stresses without flowing [54]. A number of authors have approached this problem by waiting between 20 and 60 minutes prior to mixing and depositing the top layers [17,18,20,24] (see Table 1). This method of short time-delayed casting takes advantage of the thixotropic behaviour of concrete, i.e. the natural increase in concrete yield stress with the time at rest. Since within the first hour after mixing the effects of cement hydration are generally limited [55], a relatively good bond between layers can still be achieved. A time delay can be avoided if the mix rheology is designed such that the wet state system is stable throughout casting. For example, Roesler et al. [19] poured the top layer immediately after casting the bottom layer to promote a good bond between the two mixes. Control of the wet deformation of the layers was achieved by selecting mixes with sufficient inner stability and stiffness in the fresh state. Local flow at the interface can also be caused, or amplified, by externally applied vibration. A major problem with fresh-on-fresh casting is the lack of established analytical and numerical frameworks available to predict the effects of material properties, geometry, and applied vibration on the stability of the concrete layers. To this end, more research is needed to develop improved predictive models of the mechanisms driving the fresh state deformations. A further practical disadvantage of fresh-on-fresh casting is that pouring multiple concrete mixes in a limited amount of time may require the use of multiple concrete mixers. This can complicate construction logistics due to material sourcing and delivery time sensitivity, as well as require more complex plant arrangement.

Vertical layers

Relatively little attention has been paid to the possibility of using fresh-on-fresh techniques to cast vertical layers of material. However initial pilot studies have demonstrated the feasibility of casting vertically layered concrete elements. These generally rely on temporary movable panels to demarcate the vertical layers. However, instabilities may occur when a panel is removed while the mixes are in the fresh state. These will depend on factors such as differential heights, differences in mix density and the rheological parameters of the mixes. A summary of literature related to vertically cast graded elements is presented in Table 2.

Table 2 Fresh-on-fresh casting of vertical layers of concrete: pilot experiences

Year	Reference	Element type	Material Layer 1	Material Layer 2	Casting equipment	Design concept
1976	[56]	Slab	Normal concrete	Low strength, decorative concrete	Apparatus composed of 2 hoppers	Production concrete blocks having a decorative surface
2016	[32]	Beam	Normal concrete	Low strength concrete	Removable vertical panels	Weight optimization
2019	[57]	Layered prism	Normal mortar	Foamed mortar	Removable vertical panels	Study of the fresh state stability of vertical layers.

In 1976, Yamashita et al. patented an apparatus for casting concrete slabs composed of three vertical layers that can be subsequently split to obtain concrete blocks with a decorative surface, as shown in Figure 15 [56]. The invention allows two external layers of structural concrete to be cast such that they bound a relatively weak inner core (see vertical layer of material B in Figure 15a). The hardened layered slab can then be cut through the inner core and split into two separate blocks having a rough decorative surface (Figure 15b). Two different hoppers hold the materials to be poured in an auxiliary frame which is initially located under the hoppers to collect the materials (position A in Figure 15c). The auxiliary frame is an open box, divided into three sections by two vertical panels (see Figure 15e). Once the auxiliary frame is filled with the two materials, the bottom openings of the two hoppers are closed. The frame is then moved horizontally over a bed member to a position directly above the mould (position B in Figure 15c). This allows the two materials to be packed into the moulds under the effect of gravity.

This system is designed to cast relatively thin concrete slabs using a pair of concrete mixes with similar densities. Thus, fresh state instability phenomena related to the difference in weight between the two mixes are minimized. However, since no mechanical system controls the flow of the concrete for the external layers, the operation and precision of the apparatus are expected to be highly sensitive to the rheological properties of the material.

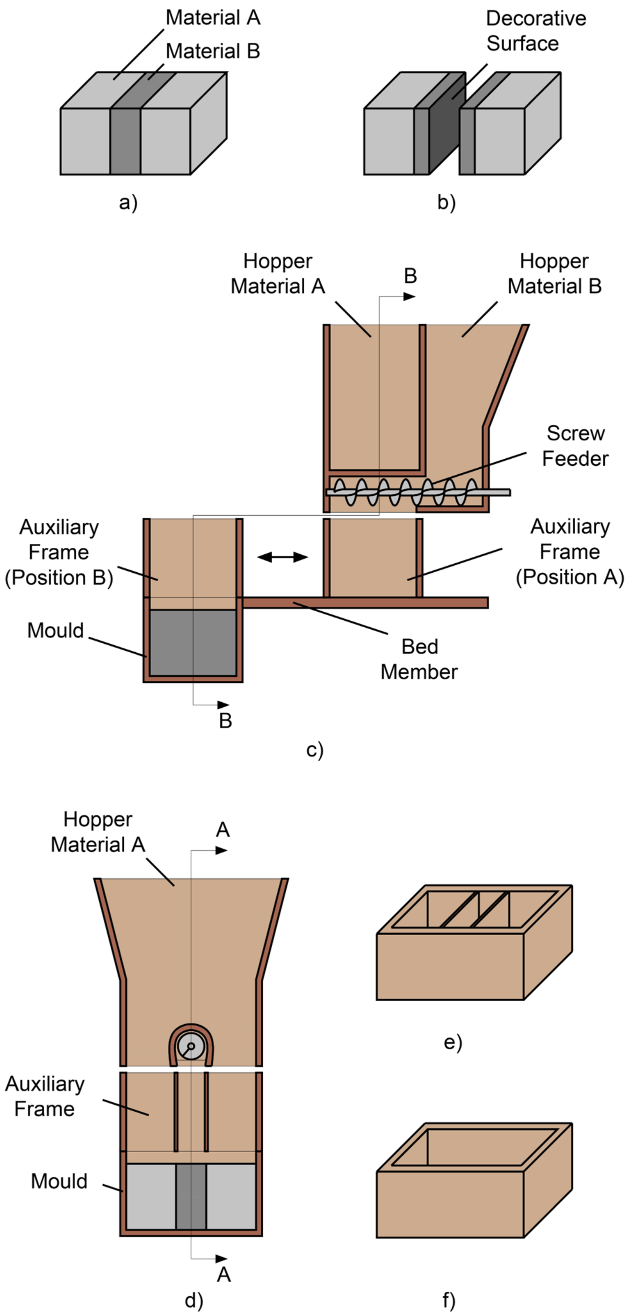

Figure 15 Early apparatus for moulding vertically layered concrete elements patented by Yamashita et al. in 1976 [58]: (a) produced composite slab, (b) concrete blocks obtained by splitting the slab, (c) section A-A of the apparatus, (d) section B-B of the apparatus, (e) auxiliary frame and (f) mould.

Heinz et al. [30] cast full-scale reinforced concrete elements composed of horizontal and vertical layers of different mixes with the aid of removable vertical panels (see Figure 16). The prototypes were composed of three concrete mixes with different degrees of porosity. The casting sequence is schematically shown in Figure 16a-d. First, a low-porosity horizontal layer of concrete was cast (see Figure 16a). Then, two vertical metallic panels were fit into the mould to demarcate three different regions in the longitudinal direction (see Figure 16b). High porosity concrete was cast in the core region, where relatively low stresses where expected to develop. A medium porosity mix was used in the lateral regions, where more demanding stress states were expected. The vertical panels were then removed (Figure 16c) and a low-porosity horizontal layer was poured on top (Figure 16d). It is worth noting that this study minimizes fresh state instability phenomena following the panel removal by using relatively stiff concrete mixes. The elements are then carefully vibrated to ensure a good bond between the vertical layers without compromising the designed spatial variation in material composition.

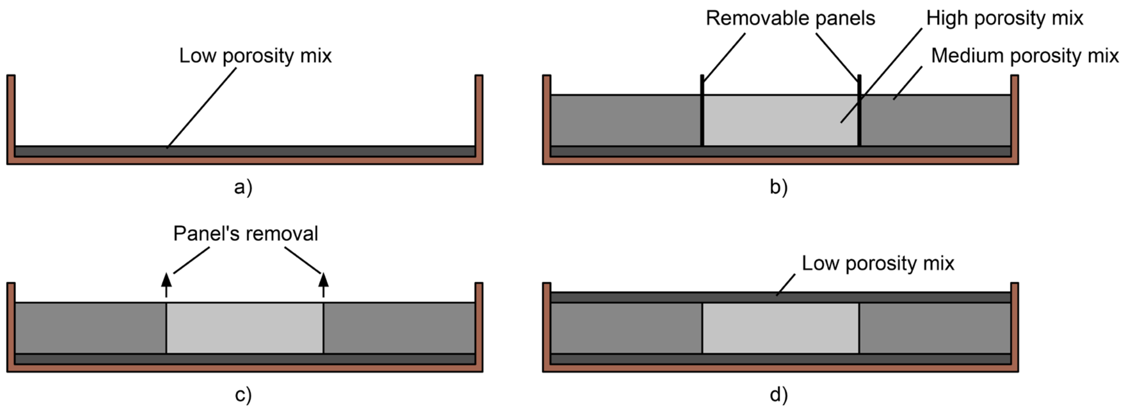

Figure 16 Casting sequence for the layered beams realized by Heinz et al. [30]. Adapted from [30].

Torelli and Lees [57] adopted a similar concept to cast small scale prisms composed of two vertical layers of different concrete mixes (see Figure 17). Specifically, removable panels were used to separate the different mixes during casting and were then removed for the two materials to come into contact (see mould equipped with removable panel shown in Figure 17). The primary aim of this study was to identify material parameters that drive the mechanical instability of two vertical layers of fresh concrete in contact.

Torelli, G., Giménez Fernández, M., & Lees, J. M. (2020). *Construction and Building Materials*. *V* 242, 2020, 118040
https://doi.org/10.1016/j.conbuildmat.2020.118040

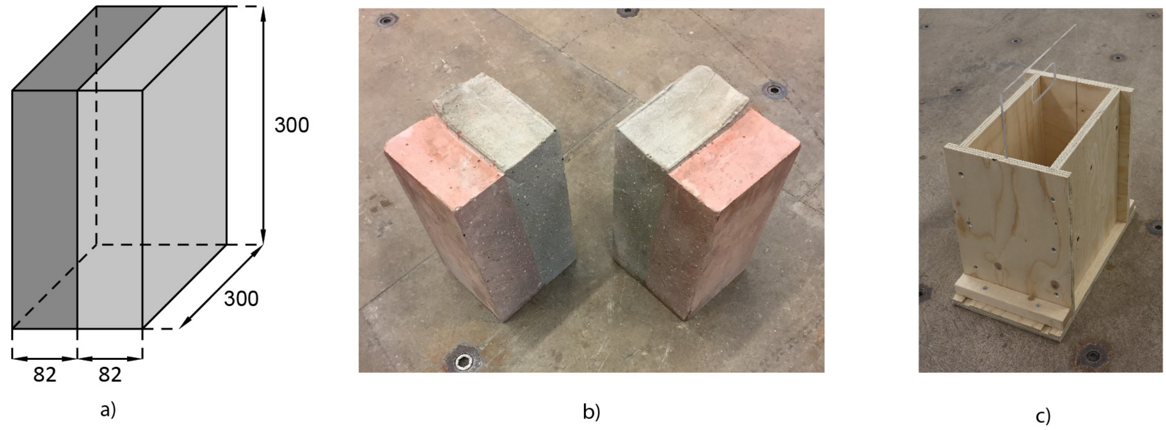

Figure 17 Prisms composed of two vertical layers of different concrete mixes realized by Torelli and Lees [57]: (a) geometry of the prisms, (b) layered prism cut in half, and (c) mould equipped with a removable panel.

As with horizontally layered elements, a limitation of fresh-on-fresh casting of vertical layers is that the final geometry of the layers may be significantly affected by concrete flow occurring in the fresh state. Flow can occur when, once in contact, the mixes are not stiff enough to withstand the shear stresses generated by their difference in density [57]. Thus, the flow of the fresh layers must be accurately controlled by selecting adequate concrete mixes. If vibration is needed, care must be taken to avoid vibration-induced flow. An additional limitation of the above-mentioned vertical layering methods is the inability to cast vertical layers whose interface intersects pre-placed reinforcing elements. Thus, these techniques are limited to unreinforced regions of concrete and regions reinforced only in directions parallel to the interfaces between layers. Furthermore, the integrity and characteristics of the interface will depend on both the process and the extent of intermixing. The use of temporary panels causes alignment of aggregates in the horizontal direction as schematically shown in Figure 18a. If the two mixes are relatively stable, such alignment may still exist after the panel removal, thereby leading to an interface that is not crossed by aggregates (see Figure 18b). Hence, further research is required to understand the effects of the local aggregate layout on both the local fracture properties and the effectiveness of the bond between different materials.

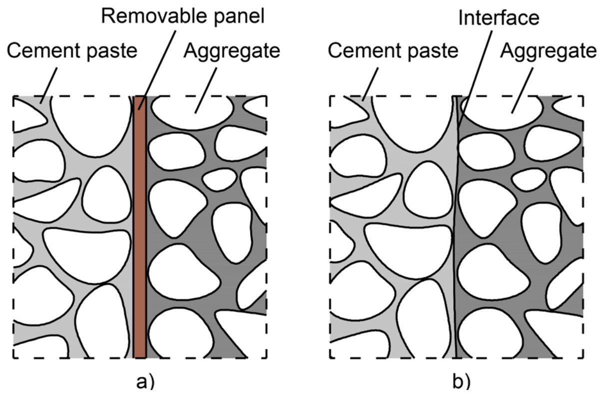

Figure 18 Schematic representation of a vertical interface without crossing aggregates. Aggregate layout on casting (a) and following panel removal (b).

3.2 Continuously graded concrete

Recent advancements in robotics have promoted the development of automated manufacturing methods to produce continuously graded concrete elements. Although still in their infancy, these technologies have the potential to define the next era of concrete design and manufacturing. In this section, the opportunities of employing additive manufacturing, graded spraying and controlled segregation techniques to achieve continuous concrete gradation are discussed.

3.2.1 Additive manufacturing

Additive manufacturing, also known as 3D printing, is the automated process of fabricating objects from 3D model data by progressively adding layers of material [59]. In recent years, significant improvement has been made in 3D printing of concrete at a structural scale [60–64]. Large-scale robotic arm systems were recently developed that can automatically store, mix, convey and deposit cementitious materials at rates greater than 45 kilograms/hour, thereby making 3D printing more competitive in the construction industry [64]. Comprehensive reviews of 3D printing techniques for construction are presented in [65] and [66]. 3D printing technologies have been traditionally developed to manufacture homogenous concrete elements [65]. However, a major potential benefit offered by 3D printing is the ability to create graded components by dynamically varying the composition of the deposited material. This concept, referred to as Local Composition Control (LCC) [67] or Variable Property Design Fabrication (VPDF) [68], has recently been applied to 3D printing of polymers and thermo-plastic materials. Preliminary experiences with these materials have demonstrated the potential for successful applications with concrete.

In 2010, Oxman patented a 3D printing apparatus enabling the extrusion of a mixture of thermoplastic materials whose composition varies in a continuous gradient [69]. The apparatus allows a plurality of materials to be heated, mixed and extruded from a nozzle (see scheme reported in Figure 19a). The ratio of the materials being mixed may be dynamically varied. With reference to Figure 19a, different materials are first inserted into heating chambers by mechanical actuators. The materials are then melted in the heating chambers and mixed in the mixing chamber. The resulting mixture is finally extruded though a nozzle. The application of this principle to print continuously graded concrete is an area of active research [31].

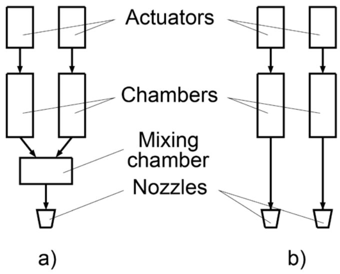

Figure 19 Block diagrams of 3D printing apparatuses to realize functionally graded components: (a) apparatus for extrusion of graded filaments patented by Oxman [69] - adapted from [69] - and (b) apparatus for simultaneous extrusion of multiple homogeneous filaments developed at the Polytechnic Institute of Leira [70,71].

More recently, a 3D printing system, coined *RapidConstruction*, has been developed to fabricate functionally graded components by simultaneously using two nozzles [70,71]. – as shown schematically in Figure 19b. The rate of extrusion of the two nozzles can be controlled independently, thereby allowing two different materials to be independently deposited in various locations [70,71]. Although unable to vary the composition of the deposited material in a continuous manner, the system can fabricate layered components whose material properties vary in a continuous way at a structural scale. The potential of this technology was demonstrated by fabricating elements composed of alternate filaments of different polymers.

It is therefore reasonable to infer that 3D printing will introduce vast opportunities to create continuously graded concrete elements. However, additional research and developments are needed not only to extend the concept of 3D printing of graded elements to concrete, but also to overcome the inherent limitations of current technologies for 3D printing of cementitious materials. These limitations include the current use of cement-intensive mixes with high embodied-carbon in 3D printing and difficulties in embedding reinforcement steel in printed concrete.

3.2.2 Graded spraying

Sprayed concrete is a casting method by which concrete is sprayed into place, rather than being poured in conventional formwork or extruded and deposited through additive manufacturing techniques. Spraying techniques may be classified into dry and wet processes depending on the concrete batching method used. In dry processes, a dry mix of cement and aggregate is propelled through a spraying nozzle, where a fine spray of water is added to the stream of materials to hydrate the cement. In wet processes, cement, aggregate and water are batched upstream and the resulting mix is pumped through a hose or pipe to a discharge nozzle. In both processes, the materials are propelled through high-pressure air.

Researchers from the University of Stuttgart developed an automated manufacturing process that allows graded concrete elements to be fabricated using a wet sprayed concrete technology [30,32,72]. The process uses two pumps that simultaneously spray two mixes with a particular selection of opposing characteristics (see Figure 20). The two pumps are integrated in a computer-controlled mobile crane. Automated control of travel speed and volumetric flow (spraying rate) of the two pumps allows for a continuous gradation of concrete properties. The authors successfully adopted this technique to manufacture concrete prisms having a graded material composition in the vertical direction. Specifically, the prisms were obtained as a series of horizontally sprayed layers with decreasing bulk density and strength.

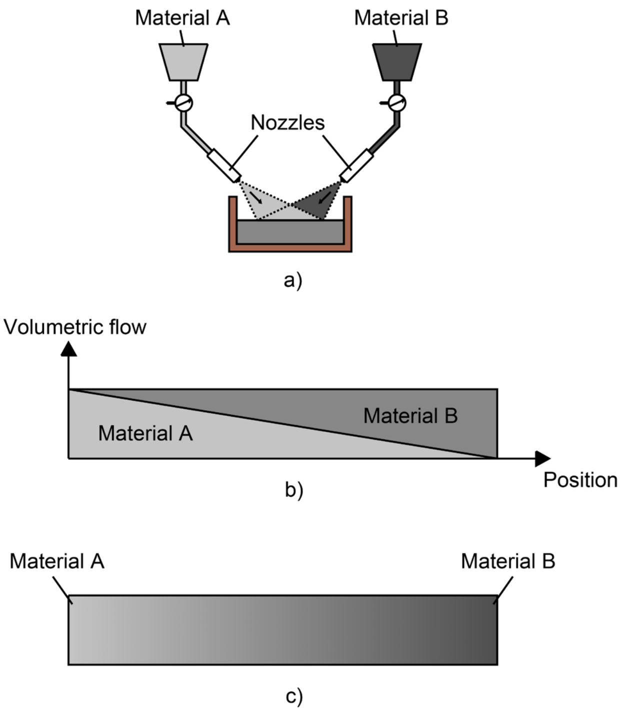

Figure 20 Graded spraying manufacturing process developed by Heinz et al. [30]: (a) schematic representation of two nozzles operating simultaneously, (b) volumetric flow allowing to achieve a linear gradation of material composition, and (c) graded concrete element with a linear gradation of material composition. Adapted from [30].

A major advantage of this sprayed concrete process is that, since the material is compacted upon impact, no compaction energy is needed. This allows for accurate control and grading precision. Furthermore, this technique can be employed for the fabrication of curved elements as the application of the material in thin layers enables concrete placement in curved formworks. An additional potential advantage is that it can be exploited both off-site and in-situ.

3.2.3 Controlled segregation

In concrete technology, segregation is the separation of constituent materials in concrete. Under the effect of gravity, the constituents of concrete tend to segregate due to differences in density. When homogeneous concrete elements are designed, concrete mixes are designed to minimize segregation. This can be achieved, for example, by limiting the fluidity of the concrete [53]. However, when non-homogenous elements are desired, segregation can be the means through which the grading of material composition is achieved. Heinz [30] et al. recently developed an automated process that allows cylindrical elements with a radially variable composition gradient to be manufactured through rotation-controlled segregation. An initially homogeneous concrete mix is placed in a hollow metallic tube. The tube is then clamped in a lathe and rotated about its axis at constant speed (see Figure 21a). Centrifugal acceleration generates the segregation radially. The rotation is stopped when the material has developed sufficient stiffness not to segregate further under the effects of gravity. The authors demonstrated the potential of this technique by segregating a rapid set concrete mix, obtaining cylindrical elements with increasing material density and strength along their radius (Figure 21b).

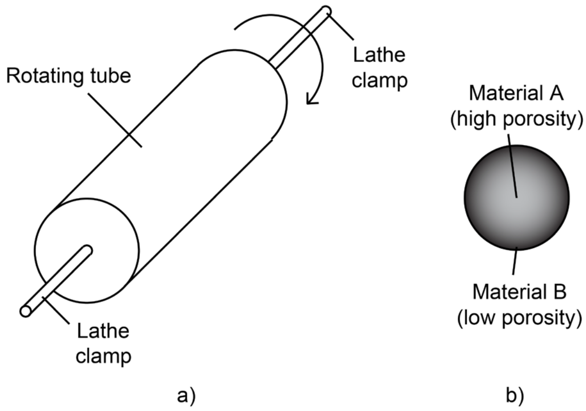

Figure 21 Rotation-controlled segregation process: schematic representation of (a) experimental set-up and (b) cross section of the obtained graded specimen. Adapted from [30].

An advantage of this process is that it enables the manufacture of graded cylindrical geometries that would be technically difficult to achieve with additive manufacturing or graded spraying. However, a main limitation is that rotation-induced segregation can only be adopted to segregate the heaviest particles toward the external surface of the cylinders as the migration of the constituents strictly depends on their difference is weight. Hence, only concrete cylinders with increasing material density along their radius can be produced. In addition, since a constant-speed rotation must be applied until the concrete has developed sufficient stiffness, the manufacturing process can be energy intensive, thereby potentially offsetting carbon-emission savings achieved through concrete gradation.

4 Fresh and hardened state design and analysis

The inherent topological complexity of FGC elements results in specific design and analysis challenges. The design of graded elements must account for the effects of the desired spatial variations in material composition on both the fresh and hardened state behaviour of concrete.

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4.1 Fresh state behaviour

When the desired spatial variation in material composition is associated with a variation in material density, shear stresses may develop that cause heavier materials to flow underneath lighter ones. This phenomenon is referred to herein as global instability in the fresh state. Plausible instabilities for horizontally and vertically layered concrete are schematically represented in Figure 22. An accurate understanding of the relationship between rheological properties, density of the materials, geometry and global instability is crucial to control the fresh state behaviour of FGC and associated production process.

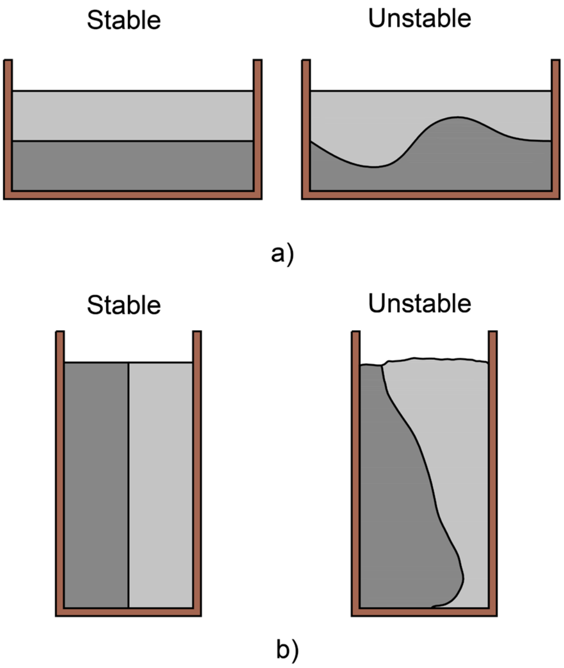

Figure 22 Schematic representation of stable and unstable layered concrete: (a) horizontal layers and (b) vertical layers.

When homogenous concrete elements are manufactured, the fresh state properties of the mix are tailored to the intended casting method. In conventional concrete casting, the material must be able to flow to fill a mould. In the case of stiff concretes, vibration is typically applied to achieve this. Vibration appears to temporarily lower the yield stress of fresh concrete that subsequently flows under its own weight [73,74]. Although vibration is needed for the compaction of fresh concrete into formwork and around reinforcement, excess vibration may result in local instabilities such as bleeding and segregation. If, however, the material is fluid enough to flow under its own weight, vibration is not necessary to achieve good compaction. This material is referred to as

Self-Compacting Concrete (SCC). Low yield stresses of SCCs mean that they can be prone to bleeding and segregation even in the absence of vibration. Thus, their inherent fluidity must be limited to avoid local instability phenomena. Similarly, in the case of concrete spraying, the mix should be fluid enough to be pumped and sprayed but stiff enough to avoid local instability phenomena. The fresh state material properties must be carefully tailored also in the case of 3D printing [75]. Indeed, mixes for 3D printing must be fluid enough to be pumped and extruded through a nozzle head, but stiff enough to hold their own weight. Furthermore, depending on the deposition and tool-path design, 3D printed cementitious materials must then set sufficiently quickly to hold the weight of subsequent layers.

In functionally graded components with a gradation in material density, additional requirements must be met in the fresh state. The rheological properties of the materials must be tailored to control the fresh state deformations driven by density differentials. That is, the fluidity of the materials must be limited to avoid global instability phenomena.

Global instability mechanisms in layered FGC were examined by Torelli and Lees [57]. The authors investigated the fundamental problem of fresh state stability of concrete prisms composed of two vertical layers (see Figure 17) through an original limit-state modelling approach based on plasticity theory. The model was validated against experiments tailored to invoke stable and unstable behaviour. Analytical and experimental results showed that the fresh state stability of two concrete columns improves with the increasing sum of the yield stresses of the two materials and with decreasing difference in density. Moreover, the study demonstrated that plasticity theory can be generally employed to assess the stability of layered concrete elements, thereby opening up the possibility to apply their plastic approach to a wide range of topologies.

The fresh state behaviour is also time and process-dependent. More experimental work is required to identify the parameters driving the behaviour of horizontal layers and continuously graded concrete and further, reliable and robust numerical frameworks need to be developed and validated. Established computational techniques exist to perform generic multiphase fluid flow simulations, including Volume of Fluid (VoF), Lagrangian Multiphase (LMP) and Discrete Element Method (DEM), and could be extended for this purpose but their ability to capture the fresh state behaviour of FGC needs to be demonstrated.

4.2 Structural analysis in hardened state

One of the main drivers behind the realization of FGC elements is to demonstrate material savings. However, to exploit this opportunity in practice, suitably accurate analysis methods must be adopted as overly simplistic or cautious approaches generally lead to over-design. This can result in significant material wastage that might frustrate the savings potential offered by functional gradation. Although technically possible, accurate analysis of these non-standard structural elements may require advanced or novel modelling approaches for which specialist knowledge is necessary. This section discusses available numerical and analytical tools for the assessment of layered and continuously-graded concrete and areas where further research is needed.

4.2.1 Layered concrete

Provided that the layer interfaces do not introduce planes of weakness or preferential deterioration mechanisms, layered concrete systems can be analysed using a step wise-variation in material composition. This simplifies the definition and assignment of material properties. In finite element analyses, for example, accurate models of the actual spatial variation in material composition may be obtained by assigning different homogeneous properties to each group of finite elements representing a different layer [76,77]. Furthermore, the widespread use of layered concrete elements in the precast industry has led to the development of well-established standards for the structural design of layered elements acting compositely [40–48].

Nevertheless, these approaches are only fully justified when a composite behaviour is guaranteed by an efficient bond between the layers. In a well-designed fresh-on-hardened layered structure, effective bond is generally achieved through transverse reinforcement. What remains unclear is the extent to which fresh state material properties, casting methods and strain incompatibilities affect the bond in the case of fresh-on-fresh casting. Hence, additional experimental research is needed to develop the necessary knowledge required to produce suitable design guidelines and numerical strategies for the assessment of layered concrete elements cast fresh-on-fresh. The explicit modelling of an interface is plausible but introduces further complexity and a need for appropriate material, transport and fracture models for the interface zone.

4.2.2 Continuously graded concrete

The inherent topological irregularity of bespoke continuously-graded concrete elements make numerical simulations a key tool to assess their structural behaviour. The finite element method is by far the most established numerical technique to model functionally graded structures but boundary elements and isogeometrical formulations have also been employed [78–82]. In concrete applications where damage analyses and crack path predictions are important, the behaviour of the material is predicted through local damage and fracture criteria. Thus, an accurate assessment of the local stresses and strains is key to obtain reliable results [83–85]. When the material composition varies along one or multiple directions, the local stress and strain states strictly depend on the gradient of elastic properties. Consequently, numerical models must be defined to fit the real spatial distribution of elastic properties as accurately as possible. This can be achieved through various techniques.

A widespread approach to discretize the spatial variation of material properties is to assign different homogeneous elastic properties to each finite element [29,86–91]. In other words, multiple dissimilar materials are defined and assigned to finite elements and a step-wise constant approximation to the property field is obtained at the element borders. The accuracy of the discretization of the material properties fields and the numerical results depends on the mesh size [87]. A successful application of this method to study the behaviour of continuously-graded concrete is reported, for instance, in [29]. The analyst must, however, always weigh up the gains in accuracy caused by a mesh refinement against the corresponding increase in computation time.

More refined and computationally efficient techniques to match the material properties of functionally graded materials have been developed but they have not yet been widely applied to the study of continuously-graded concrete. These methods include: the definition of temperature-dependent material properties and subsequent assignment of an initial, constant temperature distribution that matches the gradient in material properties over the calculation domain [92]; the definition of subroutines that allow an arbitrary field of material properties to be directly assigned to the Gauss points of the elements [83]; the adoption of graded finite elements, i.e. finite elements that incorporate a spatially varying material property field [93–99]. More research is required to validate the ability of these techniques to accurately match the properties and model the behaviour of continuously-graded concrete.

Although numerical simulations represent the main tool to assess the behaviour of bespoke FGC, some cases exist where a regular distribution in material properties allows for an analytical assessment. For example, Shota et al. [100] showed that iterative methods analogous to those used for homogeneous elements can be adopted to assess the flexural strength of beams with a material gradation in the direction normal to the neutral axis. However, the general lack of simple analytical techniques currently represents a barrier to the formulation of design codified guidelines and consequent implementation of continuously graded concrete in construction.

5 Summary and conclusions

Concrete is the most widely used construction material in the world. The industrial production of cement, the key constituent of concrete, is associated with around 5% of global human-made carbon emissions. Hence, technologies aimed at minimizing the use of cement and concrete while keeping unaltered the innate strength and durability properties of concrete structures need to be developed. A critical review of Functionally Graded Concrete (FGC), with a particular focus on structural applications, production processes, and analysis and design methods was presented. Two main topologies of FGC, namely layered and continuously-graded concrete, were defined.

Material savings of up to 40% have been shown possible through functional gradation of concrete. Design objectives for functional gradation include: cement reduction in selected zones to meet a desired strength; controlling the post-fracture behaviour of concrete by employing high quality materials only in the regions governing failure; the use of low-permeability and multiple-cracking material in the peripheral regions of reinforced concrete elements to delay the ingress of aggressive substances and consequent steel corrosion; minimisation of cracking associated with hydration heat in mass structures by grading the cement content of the material; weight minimisation through a spatial variation in density, and optimising the thermal performance of concrete elements by realising an insulating concrete layer to reduce energy consumption and associated carbon emissions.

Recent advancements in robotics have unveiled the potential to automate the manufacturing of FGC elements, thereby reducing construction costs and time, and boosting productivity. The production of FGC has also the potential to transform the construction industry and, consequently, the architectural design of concrete structures by introducing new topologies and material interfaces. Existing production methods for layered and continuously-graded concrete were explored. Owing to their widespread use in the precast industry, fresh-on-hardened casting techniques are well-developed. Emerging fresh-on-fresh layered casting techniques have significant potential in civil engineering applications. The main potential advantages of fresh-on-fresh casting are the opportunities to achieve good bond between the layers and reductions in the manufacturing time. Continuously graded concrete can be realized through additive manufacturing by dynamically varying the composition of the deposited material, graded spraying or, for cylindrical specimens, rotation-controlled segregation. A major challenge in the production of fresh-on-fresh FGC elements is the control of their fresh state deformations and further research is required to understand the behaviour of horizontally-layered, vertically-layered and continuously-graded concrete. Furthermore, the ability of existing computational fluid dynamics techniques to model the behaviour of FGC in the fresh state needs to be validated against experiments.

The relatively simple topology and well-established use of fresh-on-hardened layered concrete in the precast industry means that existing structural analysis techniques can in principle be extended to model functionally layered fresh-on-fresh concrete. A caveat is the reliance on the integrity of the interfaces between the layers. The introduction of preferential pathways for the diffusion of aggressive substances, interface cracking or planes of weakness would all be detrimental. Hence, further investigations are needed to identify the parameters affecting the bond between layers in the case of fresh-on-fresh casting. This will potentially enable a safe design of optimized concrete structures with an increase in productivity. Although technically possible, an accurate structural analysis of continuously graded concrete structures can require advanced or novel modelling approaches and specialist knowledge. The development of simple analytical techniques to model FGC would remove a barrier to implementation in the construction industry and help to drive a change in ethos towards cement minimisation.

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