Development of Weight-Optimised, Functionally Graded Precast Slabs

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Introduction

Our built environment not only consumes about 35% of total energy and causes 35% of total greenhouse gas emissions. It also utilises 60% of our resources and is, at least in Central Europe, the source of over 50% of total bulk waste. Thus, the construction industry plays a crucial role in either preserving or destroying our planet (Sobek et al., 2010). It is also obvious that we have to finally turn words into action amidst well-known facts such as global warming, resource depletion, rising energy costs and the increased destruction of our ecosystem. The construction sector can contribute to significantly reducing global resource consumption, waste generation, emissions and energy consumption by developing more lightweight structural components whose constituents can be cleanly sorted and recycled individually. A major step towards developing such components is to functionally grade the materials these components consist of.

Functional gradation of material properties makes it possible to optimally align the internal element structure with the specified requirements. Accordingly, zones subject to high loads use high-strength materials whereas areas under comparatively small loads can use porous materials with pore sizes and/or densities that are adjusted to loading levels either continuously or in a stepwise manner.

The application of the concept of functional gradation to concrete or reinforced-concrete elements opens up promising prospects particularly if the individual structural component is to meet inhomogeneous or varying requirements. Possible fields of use include structural components predominantly subject to bending, such as beams and slabs, but also columns and walls as well as pipes, structural shells and elements in freely designed shapes. Floor slabs and external wall panels have proved to be particularly suitable for applying the concept of functional gradation.

Current state of research

Functionally graded materials are materials that exhibit a continuous change in one or several of their parameters, such as their hardness, density, porosity or chemical composition, over a defined length in at least one spatial direction (Rödel, 1996). Nature provides a wide range of examples of this principle of optimisation, including graded cell-like structures (spongiosa) within bones and functional transitions in the cellular structure of plants or of the human skin (see Fig. 1).

Fig. 1: Section of a femoral neck bone as an example of natural density-graded structures

In 1971, researchers at the Massachusetts Institute of Technology (MIT) laid the foundations for this area of research by introducing the concept of “functionally graded materials” (FGM). The DFG Priority Programme 733 on “Functionally Graded Materials” (1995-2003) (Kieback et al., 2003) primarily examined ceramic-metal, metal-metal and ceramic-polymer gradations that extended over a distance ranging from several hundred micrometres to several millimetres in the related research projects.

The development of functionally graded concrete gave rise to a new field of research that was first pursued by ILEK (Institute for Lightweight Structures and Conceptual Design at Stuttgart University). Basic research was undertaken in the project “Herstellungsverfahren und Anwendungsbereiche für funktional gradierte Bauteile im Bauwesen” [“Manufacturing Methods and Fields of Use of Functionally Graded Structural Components in Construction Engineering”] (“Gradientenwerkstoffe im Bauwesen”; “Functionally Graded Materials in Construction Engineering”) (Heinz et al., 2011). The project “Entwicklung gewichtsoptimierter funktional gradierter Elementdecken“ [“Development of Weight-Optimised, Functionally Graded Precast Floors”] (“Gradierte Elementdecken”; “Functionally Graded Precast Floors“) (Herrmann and Sobek, 2014) examined the use of functionally graded concretes for structural components in bending. We are grateful for the funding of both projects within the “Forschungsinitiative Zukunft Bau” [“Building our Future” research initiative] launched by the then Federal Ministry of Transport, Building and Urban Affairs. Current research is concerned with continuously improving the automated production processes as part of the DFG Priority Programme 1542 “Leicht Bauen mit Beton” [“Lightweight Construction with Concrete”]. For this purpose, the subproject on “Optimalstrukturen aus funktional gradierten Betonbauteilen” [“Optimal Structures made from Functionally Graded Concrete Components”] has been initiated in which ILEK is cooperating with the Institute for System Dynamics and the Institute of Construction Materials at Stuttgart University.

Mix designs for functionally graded concrete

Concrete components can be functionally graded by arranging varying porosities, adding a diverse range of aggregates (including hollow spheres or aggregates with selected levels of rigidity), using various types of concrete or combining these methods with each other. In the first step, two extreme concrete mixes are defined to determine relevant boundary conditions. A high-strength fine-aggregate concrete is selected as the extreme at the load bearing end of the functional gradation range. The porous extreme of functionally graded concrete, the so-called core mix, is made from a no-fines lightweight concrete mix with a porous matrix (Faust, 2003). Structural characteristics are enhanced by minimising porosity, whereas thermal insulation properties are improved and the own weight reduced by maximising porosity. Properties can be freely varied between these two mixes by adjusting porosity within the defined limits. In this project, gradation included seven steps to define trends and transitions of material properties. The characteristics of hardened concrete can be correlated to porosity. Structural parameters such as strength and rigidity decrease as the air void ratio increases, whereas thermal properties are enhanced, including a decrease in thermal conductivity λ (see Fig. 2). Testing of hardened concrete parameters of these mix designs confirmed this known dependency on bulk density.

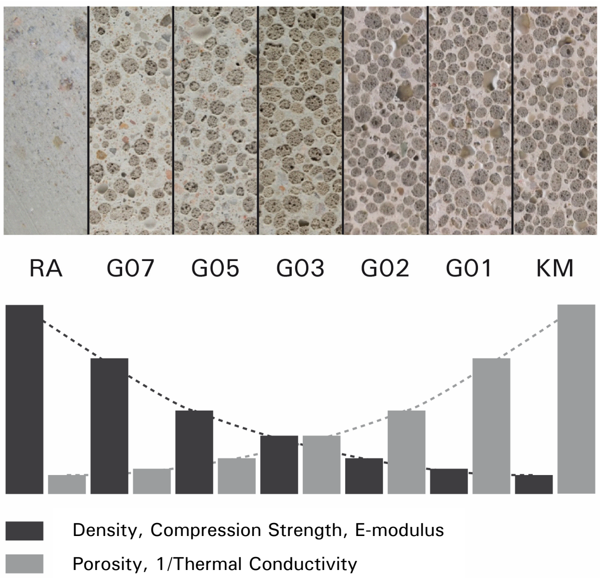


Fig. 2: Curves of hardened concrete characteristics depending on a gradual increase in porosity

Production processes for components made from functionally graded concrete

The homogeneous mix designs conceived in the first step were used to develop production processes that enable a shift from “stepwise gradation” to a virtually seamless pattern. Some of these methods are outlined in the following sections of this paper. Further tests with respect to concrete printing, controlled segregation, infiltration, graded mixing and production with reversible placeholders are described in the final report published for the "Gradientenwerkstoffe im Bauwesen" ("Functionally Graded Materials in Construction Engineering") project (Heinz et al., 2011).

Layered casting

This method allocates the individual available mixes to various areas within the element so as to meet the respective specifications. The number and thickness of layers and the mix design variation from one layer to the next make it possible to control the discontinuities in the material characteristics that occur at the interfaces of the component layers. The properties of the individual layers can be managed with pinpoint precision by selecting the most appropriate concrete mix. The wet-in-wet casting process ensures a firm bond of the layer boundaries thanks to a sufficiently fine resolution. Fig. 3 shows the production of a scaled beam from functionally graded concrete for the four-point bending test using a reverse process. The beam comprises three layers both in vertical and horizontal direction.

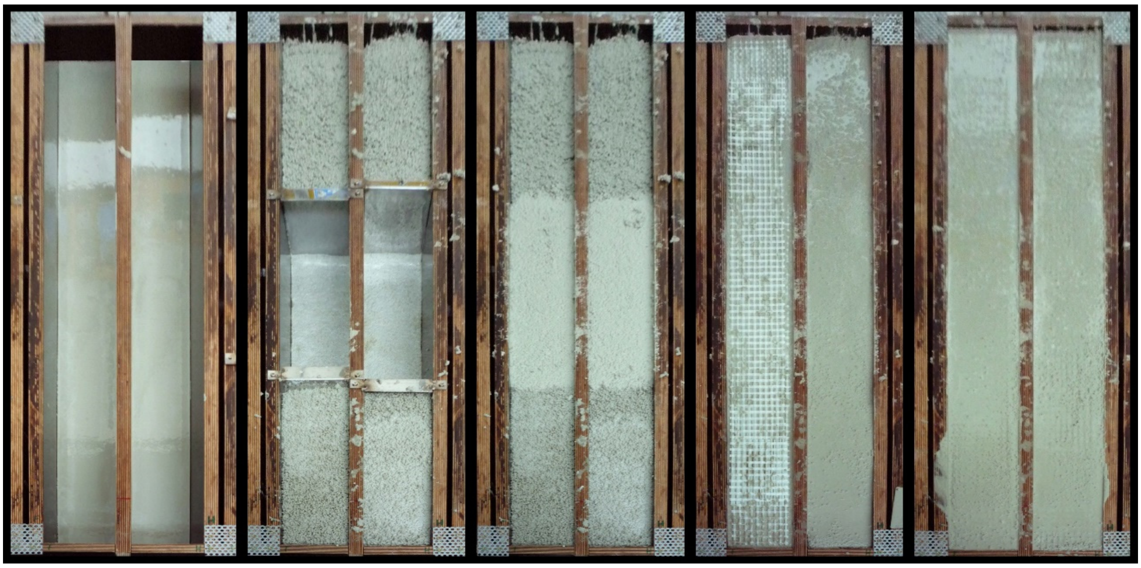
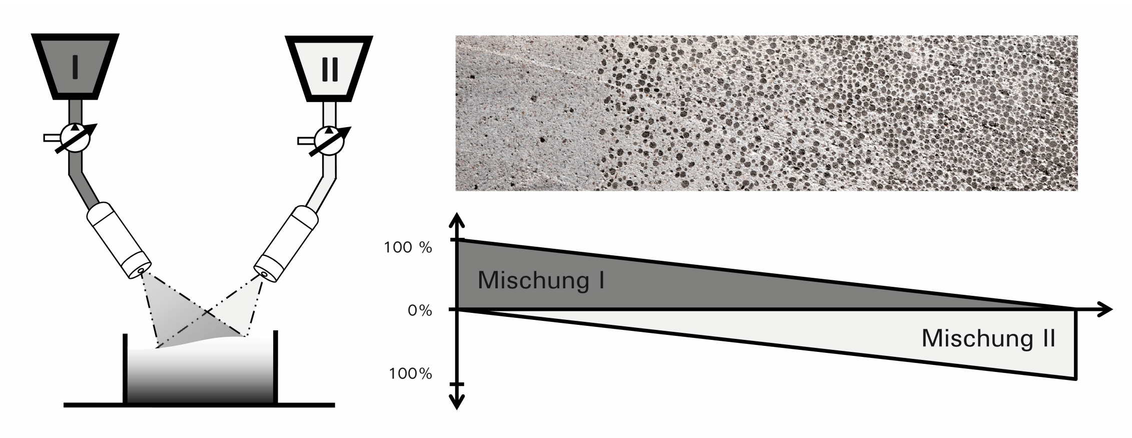


Fig. 3: Production of a functionally graded concrete beam in a layered casting process

Graded spraying technique

Compared to layered casting, the spraying method provides a number of advantages. Whereas introducing compaction energy into cast graded concrete elements may eliminate the previously defined controlled gradation, the use of the spray technique to produce graded elements does not require subsequent compaction because the concrete is compacted already upon the impact. Application of the material in thin layers enables a fine resolution and concrete placement on curved formwork. Furthermore, this process can be automated and implemented both at the precast plant and on the construction site (using large-scale robotics in the latter case).

The "Functionally Graded Materials in Construction Engineering" project included the development of a graded spraying technique using two homogeneous, pumpable concrete mixes (see Fig. 4). Gradation is established in the spray head or spray mist by adding compressed air. Volumetric flow control of the pumps enables continuous gradation from low to high strength and from heavy to ultra-lightweight, with the option to also add heat insulation properties.



a) Graded spraying b) Spray sample

Fig. 4: Schematic representation and test result of the graded spraying technique

Volumetric flow control is the main factor that determines the accuracy of the applied process. Automated control of the two pump supply lines is the only option that accurately achieves the specified material characteristics.

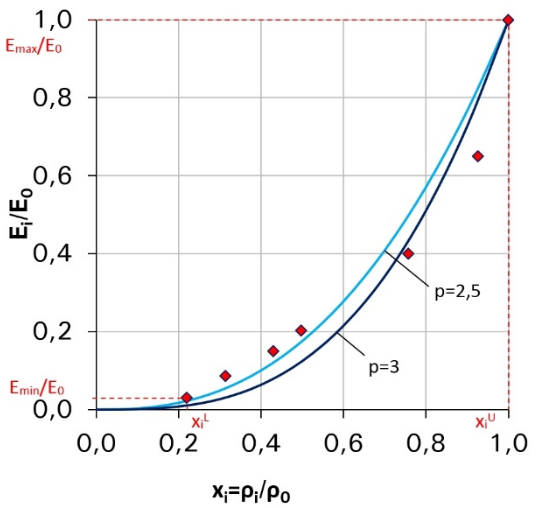
As part of the "Optimal Structures made from Functionally Graded Concrete Components" project, a manipulator is currently being developed for the production of functionally graded elements with gradation patterns that can be freely arranged within the given space. The manipulator uses the principle of graded spraying and sets varying mixing ratios to merge two extreme mixes in order to implement all properties within the resulting range. This manipulator uses a portal system to arrange the individual properties in space.

Design of functionally graded concrete components

Automated production is preceded by the design of elements with graded densities. From a structural point of view, the use of density-graded structures aims to minimise material consumption whilst transferring a given load in compliance with specified deformation limits. In this respect, one of the major challenges is to arrive at the optimal distribution of materials and properties within the structural component, which is referred to as the so-called "gradation layout". Simple structural systems can still be guided by examples from nature or parameters referred to in the literature, such as principal stress trajectories. Spatially complex structures, however, do not provide this option. Numerical routines need to be developed to accomplish this design task. Structural optimisation provides a suitable approach to achieve this goal.

Numerical optimisation relies on a non-linear material simulation that accurately describes the behaviour of functionally graded structural components. Simulations are performed using the commercially available ABAQUS finite-element software. The material characteristics of concrete are captured by the *Concrete Damaged Plasticity* material model, which is an elastic-plastic damage model to reflect the behaviour of non-reinforced and reinforced concrete. This initial simulation establishes the basis for numerical optimisation.

As part of the structural optimisation process, topology optimisation aims to achieve optimal material distribution within a defined design space. Certain portions of the material are either removed or shifted during the individual optimisation cycles. As far as reasonably possible, the remaining structure is utilised fully under a given loading. The material distribution strategy developed for this purpose is based on the SIMP (Solid Isotropic Material with Penalisation) approach (Bendsøe, 1989; Bendsøe and Sigmund, 2004), which makes it possible to introduce mean densities into the design space. This method describes the relationship between the E modulus E_i and the design variable x_i, applying the following equation:



$$E_i = (x_i)^p E_i^0, \quad p > 1$$

$$x_i = \frac{\rho_i}{\rho_i^0}$$

Fig. 5: Adjustment of the SIMP approach to the test results documented for functionally graded concrete mixes

E_i^0 is the E modulus of a solid element whereas ρ_i^0 represents its density. The exponential function used in the equation is adjusted to the exponential correlation between the rigidity and density parameters of the developed functionally graded concrete mixes (see Fig. 5). This is why only materials that can be physically produced are available during the entire optimisation process. The outcome of this approach is a density distribution that can be created with the functionally graded concrete mixes, which is referred to as gradient design. All optimisation steps take place in the linearly elastic range of the material behaviour. Once optimisation is completed, a non-linear material simulation is performed to evaluate the optimisation result in all areas of the load bearing behaviour.

This optimisation approach makes it possible to design a functionally graded structural component that weighs 42% less compared to a normal concrete flat floor slab with a 5 m span. The graded component uses reinforcing steel and complies with all specifications with respect to ultimate limit and serviceability limit states. The mass of the element can even be reduced by 62% when permitting greater deformation and using a textile carbon-fibre reinforcement whilst providing the same load bearing capacity as the solid floor slab.

The same element mass results in a rigidity increase by about 30% whilst also raising its initial crack load by 24% compared to a sandwich element with a core that is functionally graded to respond to acting shear loads. The increased rigidity of the optimised structural components compared to the reference can be explained by two main effects: first, a greater amount of rigid material is positioned in the tension and compression zones between the points of load application; second, a pressure arch or strut-and-tie structure is formed between the abutment and load introduction point. This optimisation process results in a digital blueprint that comprises densities associated with the respective spatial positions within the structural component (see Fig. 6).

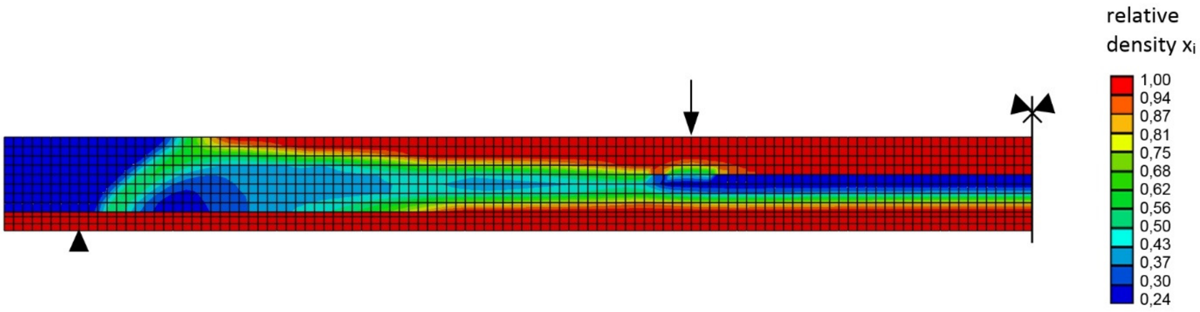


Fig. 6: Optimization result using the material distribution strategy

Fields of use of functionally graded concrete

Functionally graded floor slabs

In building construction, the own weight of floor slabs accounts for up to 70% of the total structural mass. Both a sufficiently high reinforcement ratio in the floor slabs and appropriately designed elements such as columns, walls and foundations are necessary to transfer these high inherent loads. At the same time, large areas of conventional solid concrete floors are subject to very minor loads or no loads at all. It thus appears logical to apply the principle of functional gradation to floor slabs. Concrete strength can be reduced significantly in areas subject to comparatively small amounts of compression, which suggests, for instance, the inclusion of zones with high porosity and thus lower bulk density. This design leads to a considerable reduction in the own weight of floor slabs, and thus of the entire supporting structure (Herrmann and Haase, 2013). Fig. 7 shows the internal porosity distribution within a functionally graded slab.

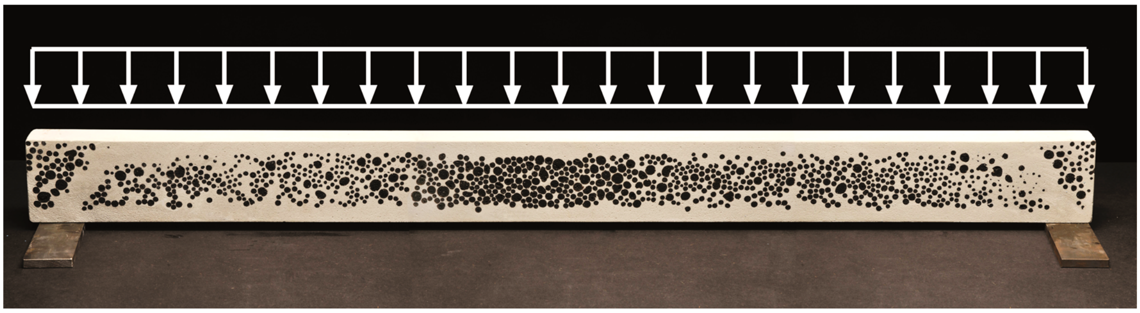


Fig. 7: Porosity distribution of a floor strip under uniform loading

Structural component tests were carried out to prove the feasibility and weight-saving potential of functionally graded precast floor slabs. Specimens produced to two different scales were tested and their load-bearing behaviour determined experimentally. The initial tests of scaled elements enabled testing of the influence of a functionally graded design and of the reinforcing materials on flexural strength. Furthermore, tests were carried out to determine shear resistance depending on shear slenderness. These tests confirmed the applied design assumptions whilst achieving a mass reduction of 59% and attaining calculated load-bearing capacities. Subsequent tests of true-to-scale elements revealed an influence of the element scale on its shear resistance. Mixes with greater strengths in the core zone subject to shear were required compared to the above-described tests of scaled elements, which reduced the weight saving to 43%. It was found that the functional gradation of precast elements has a major influence on their rigidity in State I, as well as on their initial cracking load. In State II, however, the rigidity of structural components primarily depends on the type of reinforcement used (Herrmann and Sobek, 2014).

Functionally graded external walls

Functionally graded walls are another promising example where the principle of functional gradation can be applied to supply the bulk market. This application utilises the potential multifunctionality of functionally graded concretes whilst reducing both the weight and the CO_2 emissions of such elements. The gradation of the load-bearing and insulating functions makes it possible to design strong yet thermally efficient elements with a structurally impermeable surface that meets architectural concrete specifications. Such elements use only a single, purely mineral material that can be recycled very efficiently.

Two different designs were used to examine the behaviour of functionally graded external wall panels. Both walls were composed of five layers: load-bearing covers that were as thin as possible, graded transitions and the core layer with excellent thermal insulation properties. The first wall design (Fig. 8 a) used expanded glass as a lightweight aggregate, which resulted in a heat transfer coefficient (U value) of 0.275 W/m²K at a wall thickness of 0.40 m. This is why this single-material element can replace conventional solutions composed of concrete blocks and a composite thermal insulation system whilst providing an identical total wall thickness. The second wall design (Fig. 8 b) even exceeded the above-described values. The use of an aerogel as a lightweight aggregate enabled a U value of 0.22 W/m²K for a total system thickness of 0.22 m, which meets the specifications of EnEV 2014 [*Energieeinsparverordnung*; German Energy Saving Regulation 2014] (Heinz et al., 2011).

a) Expanded-glass concrete core
U = 0.27 W/m²K; d = 40 cm

b) Aerogel concrete core
U = 0.22 W/m²K; d = 22 cm

Fig. 8: Comparison of functionally graded wall designs

Summary

The mass of structural concrete components in bending, such as precast floor slabs, can be reduced significantly by introducing a functional gradation of the properties of concrete mixes. Yet the change in porosity over the element cross-section also enables an efficient control of thermal insulation properties. Slender wall panels can be produced when adding lightweight aggregates to the core mix that achieve an excellent thermal performance whilst meeting specified load-bearing capacities and structural heat insulation requirements. This approach thus merges both aspects in a purely mineral, multifunctional, single-material element that is easy to recycle. This method provides a solution to the current issue of multi-layer composite thermal insulation systems whose use involves the inseparable gluing of a large number of materials and layers to each other. The use of functionally graded precast elements makes it possible to return to designing and constructing single-shell, heat-insulating structural walls that meet architectural concrete specifications. Automated production processes enable the efficient manufacture of such elements. The numerical optimisation methods developed in this research provide the digital blueprint required for this purpose. Functionally graded concretes will thus be able to make a major contribution to further advancing sustainable construction in the foreseeable future.

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