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Expanding Boundaries:
Systems Thinking for the Built Environment

DESIGN-ENGINEERING-BASED AND MATERIAL-BASED IMPROVEMENT OF PRECAST CONCRETE-FACADE-ELEMENTS

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Abstract

Concrete is globally one of the most common building materials in use today. Its key qualities are the load-bearing capacity, weather resistance and fire protection. However, a lot of energy is needed to produce it. Its effective replacement by new 'greener' materials with similar characteristics is currently under research but far in the future. Thus, new concrete construction methods have the potential to reduce the energy consumption considerably in the near future. The focus of our research is, not only to optimize concrete but also to develop a strategy to produce better precast components from this material.

The main focus is directed to the optimization of load-bearing exposed exterior walls. The objective is to develop and evaluate construction methods that reflect modern day concerns such as the need for good thermal insulation, the sustainable use of resources, the reduction of wall thicknesses as well as the ability to quickly erect buildings in inner city locations with high land value. The research project focuses in particular on insulation thickness and interesting facing concrete surfaces. Openings in the thinner walls have smaller window reveals, so natural lighting is improved as well.

The results of the research project will be documented by technical drawings and photos of samples. The samples have been tested for durability, stability, and through exposure to weather.

Keywords:

Precast production; load bearing structure; dispersal; hydration retarder; design-engineering; material science; conservation of natural resources; recycling

1 INTRODUCTION

When this research was outlined in 2011, the German government had already developed strategies to limit the current effects on climate change and to encourage renewable energy. The so-called „Energiewende“ (energy revolution) [1] was formulated after the nuclear power plant incident in Fukushima and gave additional momentum to this research approach.

The thermal performance of insulated double-wall concrete prefabricated elements can easily be improved. Fabrication in controlled factory conditions offers many possibilities for optimization [2]. The laboratory-like conditions allow thinner elements for higher buildings.

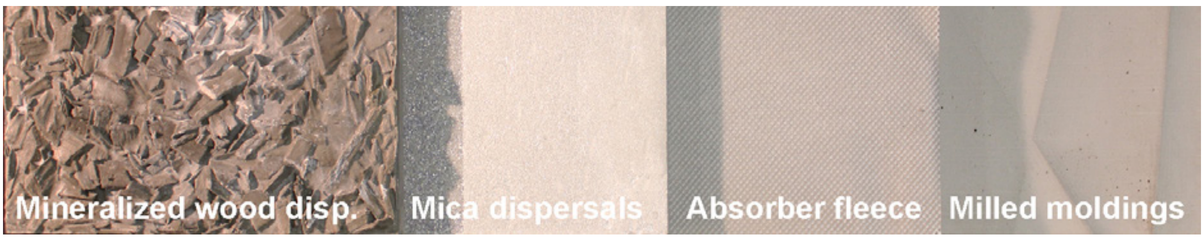

Fig. 1: UHPC-samples with different surfaces / EBB.

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In addition, prefabrication allows the use of dispersals and can offer a variety of new concrete surface treatments.

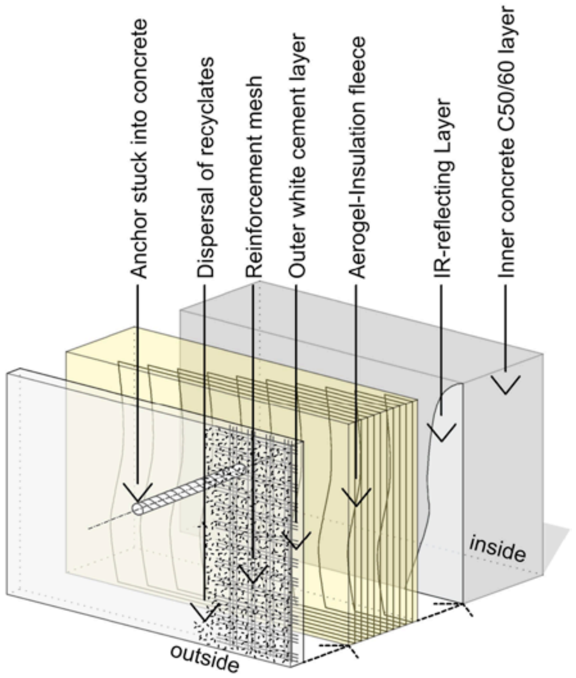

Fig. 2: Construction of the precast element / EBB.

2 MATERIALS (OR DATA) AND METHODS

In order to optimize the precast process, technical potentials should be combined to achieve efficient and convincing constructions. To assist the development of variations adjustable "levers" are defined that describe the solution spectrum: load-bearing effect, the connection between the outer and inner shells, the avoidance of solid sections through the use of filling materials, concrete composition, reinforcement, insulation and surface engineering. Samples of individual solutions are produced in mini trials to ensure feasibility. In particular, the concept of a double skinned composite construction is researched, whose elements permit integrated load-bearing. Promising options are selected and evaluated. Connecting details are developed and wall sections will be produced at full scale. Theoretical assumptions are practically tested on these preproduction mockups. The most successful approach is selected and worked up into a system through the further development of the sketched details, proposed materials and construction elements. The system limits for the wall are defined on the basis of the German EnEV 2016. The research goal shall be achieved by the work program:

- Interdisciplinarity:
  Specialists' expertise will be incorporated into each procedural step in the development process.
- Alternative approaches:
  A range of proposals will be developed, manufactured and evaluated in accordance with the above mentioned variables.
- Systematic evaluation:
  The samples will be recorded and analysed to draw generally applicable conclusions.

3 RESULTS

The main focus will be directed to the load-bearing capacity and surface. As compared to their production on site, precast production conditions permit the creation of more complex and higher performance building elements. Using these optimal industrial conditions, this research project will strive to produce concrete with more organic, regenerable constituents and to create building elements that are more efficient by volume. At this point in time, the variables ("levers") mentioned below have been researched with the following results.

3.1 Load-bearing behaviour

Load-bearing effect: composite shell or load bearing inner shell

The load-bearing effect of the outer and inner skin as a composite allows a larger structurally effective cross section [3]. The analysis of reference projects suggests that very large stresses can be expected in the joints between inner and outer shells when there are large temperature differences for instance in winter. As a consequence, composite inner and outer shell structure is not sensible.

Connection of outer and inner shell: Material and form

The connection of inner and outer shells as a storey-wise load transfer system in the outer shell should be achieved by means of round or square sectioned glass fibre anchors, which are poor heat conductors (Thermomass®/Combar®). With only a shallow bonding depth in the thin outer shell, anchor extraction tests show that a spiral form, fluted glass fiber with a chamfered end offers the best force transfer characteristics. It is structurally sufficient when the anchors are arranged perpendicular to the transfer load, an additional diagonal anchor is not necessary.

Concrete composition

The load-bearing effect of the outer shell with variable thicknesses has been tested for different concrete strengths for buildings of 5 to 6 storeys. Initial trials with UHPC showed that this material is, due to its very short workability period in a fully automated work process, not suitable for mixing in large concreting quantities. As a result, the testing reverted to the highest performance standard concrete, grade C50/60. Nevertheless,

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structural calculations revealed a required thickness of 3cm for the outer shell and 9cm for the load bearing inner shell. Subsequent test series kept these dimensions as a basis.

Reinforcement: Material and Form

The first concrete sample elements used steel fibre reinforcement of (l/d) 09/0,15 (202,0 kg/m3), which had proved highly suitable in earlier trials with UHPC. A square mesh reinforcement (round bars of d=6mm) was proposed for use with the high performance grade C50/60 standard concrete. Thanks to the weather protected position of the element within the wall structure, concrete coverage of 20 to 25mm proved sufficient, as did a predetermined spacing of 8cm between the inner and outer reinforcement layers.

Compression test

Because of its superior workability, trials of standard concrete walls followed those of UHPC. Based on a 2.50m story height, the pin jointed top and bottom of the walls have a bending height of 2.50m. Regardless of the thickness of the walls, the eccentricity was initially limited to 1cm top and bottom. The walls are cast of a concrete that reaches an average compressive strength of at least 75 N/mm² after 28 days, with a modulus of elasticity of at least 36.500 N/mm² selected. Unless otherwise stated, only the wall thickness will be varied.

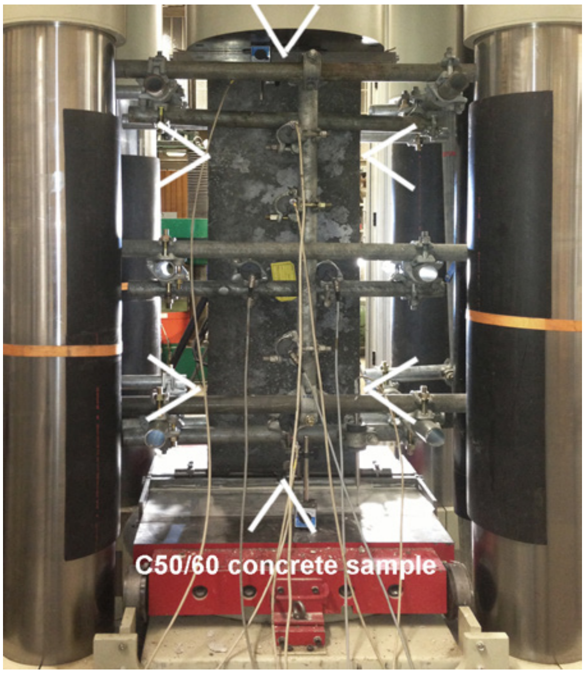

Fig. 3: Laboratory compression test / MB.

DIN EN 1992 (Eurocode 2) [4] will provide a reference for the determination of the bearing capacity of normally stressed unreinforced and lightly reinforced individual compression members and walls according to second order analysis.

$$N_{Rd} = b \cdot h_w \cdot f_{cd,pl} \cdot \phi$$

$$\text{mit: } \phi = 1{,}14 \cdot \left(1 - 2 \cdot {}^{e_{tot}}/_{h_w}\right) - 0{,}02 \cdot {}^{l_0}/_{h_w} \leq 1 - 2 \cdot {}^{e_{tot}}/_{h_w}$$

b	Querschnittsbreite
h_w	Querschnittsdicke
$f_{cd,pl}$	Bemessungswert der Zylinderdruckfestigkeit
e_{tot}	Lastausmitte gesamt ($e_0 + e_i$)

Fig. 4: Second-order analysis / MB.

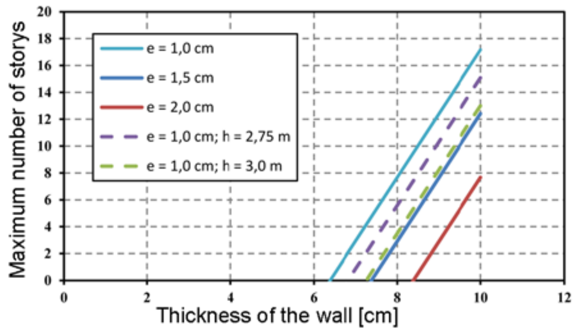

Fig. 5: Comparison of all test samples: Effect of eccentricity (e) on possible story height with varying wall thickness / MB.

120kN/m loading per floor is applied to the bilaterally supported walls, this value is derived from the self-weight of a 30cm thick floor slab and an additional load of 1.5kN multiplied by a safety factor of 1.35 and a live load of 5.0kN multiplied by a safety factor of 1.50. Thus a biaxial load transfer and a maximum span of 12m – a draw-in width of 6.0m is achieved. Obviously, these constraints must be checked for each building. It is thus recommended to select an inner wall thickness of at least 8cm; a thickness of 9cm is optimal as this permits greater eccentricity.

3.2 Material performance characteristics

Insulation: Material and Form

Today, vacuum insulation provides the highest performance of thermal insulation. Risk of damage can be reduced through its exact embedding in the concrete matrix [5]. This high performance insulation can be replaced by a more robust phenol resin based insulation at reinforcement penetration points. This reduction in performance is possible as the phenolic foam insulation in these areas achieves acceptable levels of insulation. The minor temperature differences will be evened out through the thermal transmission of the outer shell.

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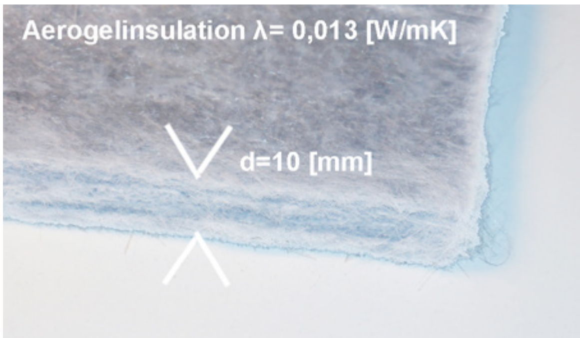

Fig. 6: Aerogel sample / EBB.

It has been revealed in the course of the project that aerogel fleece mats offer a similar coefficient of thermal conductivity along with substantially lower vulnerability. Due to the very low volume of production, the cost for these mats is still relatively high. However, a reduction in costs can be expected with increased demand and production.

Avoidance of solid sections through the use of filling materials

As part of research into the dimensioning of the inner loadbearing layer, the incorporation of additional insulation between the reinforcement anchors of the inner and outer shells was studied. This arrangement did not result in any concentration of the transmission of forces in the ribbed area provided for this purpose and thus also no increased insulation in the infill area.

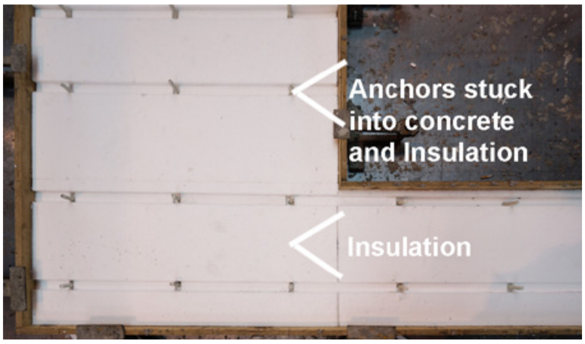

Fig. 7: Thermal insulation as a moulding / EBB.

Heat measurement

At this stage, no trials have yet taken place in a heat chamber. The test is focused on the reduction of the wall thickness and the surface quality.

IR-reflecting layer

The use of IR reflecting foil can reduce thermal transmission. During Production on the outer side of the load-bearing layer an IR-reflecting foil should be applied. This additional layer improves the insulation of about 0,3m2K/W. This is equivalent up to 10mm of conventional insulation with the common thermal conductivity of 040. The vapour resistance of the metallic foil can cause humidity problems. This has to be verified while finishing the research project [6].

3.3 Surfaces

Surface engineering

Samples with different surface types will be produced:

- A formwork of absorbent fleece (Zemdrain®), wood concrete and mineral dispersals will be studied as a new surface for the outer shell.
- A hydration retardant will be applied to the formwork, which will leave the surface dispersals visible including a thin paste-like white cement concrete mix.

As a result of its simplicity, there is potential for automation and wide range of surface options; the latter alternative will be more closely studied. For each scattering type, two samples will be produced along with an additional piece for weathering tests.

Formwork

In the industrial precasting process, moveable steel formwork tables can be used. This will simplify the even scattering of the dispersal on the formwork. During the tests, this will be done manually. 30mm high Styrofoam strips will be cut and glued onto the clean steel formwork tables. To ensure a better visibility of the mineral dispersals, the underside of the horizontal concreting formwork will be painted with a curing retarder (CR Type N Reckli®, Türkis 0,25mm Typ Mikro) to prevent concrete slurry deposits.

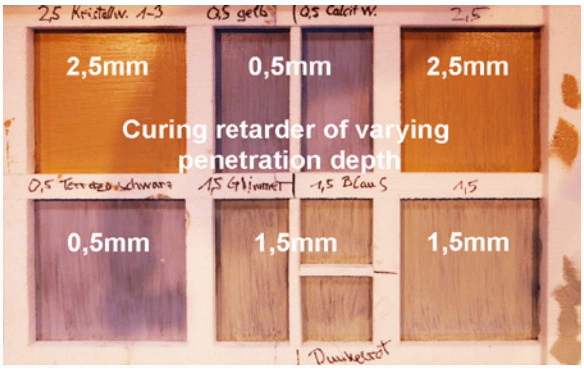

Fig. 8: Formwork table / EBB.

After application and drying time, the retardant will be scattered with a variety of mixes. The retardant with the lowest penetration depth will be combined with dispersals of all sizes:

Sample	Material	Grain size
1-2	brick granulate	2-8mm
3-4	Alkali res. Glass chippings	2-4mm
5-6	deep draw quality A-PET	varies
7-8	ABS EX. Polylac 747	varies
9-10	mineralized wood	1-5mm
11-12	brass granulate	varies
13-14	titanium granulate	varies
15-16	humus	varies

Fig. 9: Schedule with different dispersals / EBB.

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Concrete

White cement creates a neutral appearance of the visible shell. The concrete mix design of the load-bearing shell is suitably tailored to the mass mixer requirements and produced. After careful judgment, aggregates (e.g. cellulose) are gradually added on site to achieve the correct consistency. The cellulose prevents the gravel from sinking during the curing period.

Fig. 10: Formwork table / EBB.

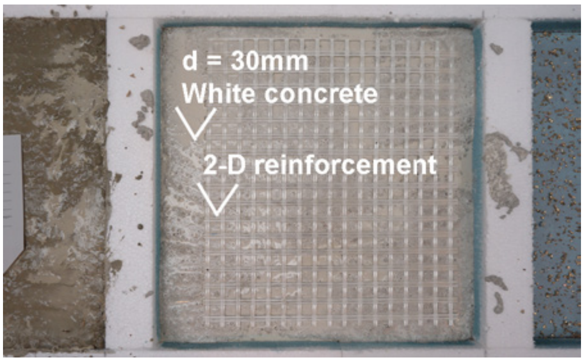

Fig. 11: Formwork table / EBB.

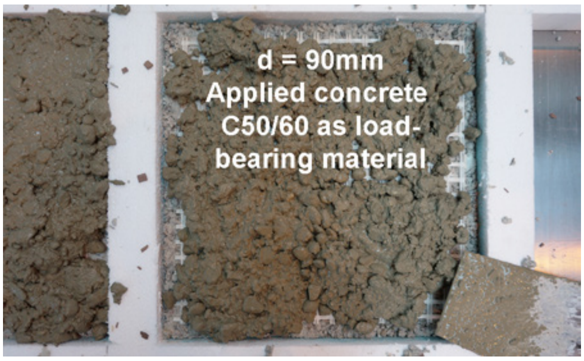

Fig. 12: Formwork table / EBB.

Concrete technology investigation

The water-cement ratio of the load-bearing shell is determined after the production by a concrete technologist.

Stripping of formwork

The formwork is stripped from the samples after a day's curing. The Styrofoam® mould is removed and the sample turned with the visible surface facing up.

Curing of surface

The visible surface is evenly cleaned of retardant and concrete slurry with a high pressure water jet.

Rule

The smaller the grain of the mineral dispersal, the smaller its optical effect and the stronger the leaching. The addition of the retardant allows the correct level of rinsing of the surface to reveal the dispersals to full advantage.

Summary and strategy

The next step is to build on the good results so far and produce full-scale test samples of the inner wall construction with insulation.

Merging of results in full-scale samples

The results of the sample production and surface enhancement encourage further investigations of full-scale samples of storey height panels. The production will be integrated into the assembly lines. The setting of the concrete mix requires the exact timing of reaction times of the curing retardant and the manufacturing process. Procedurally, the precast element is very easily and satisfactorily produced. The dispersals are evenly applied to the surface avoiding the points of contact of glass fibre reinforcement rods with the formwork table.

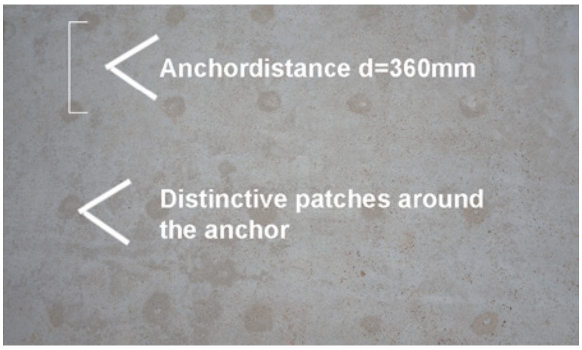

Fig. 13: View of the full-scale sample / EBB.

"Nests" and patches of darker coloured concrete appear radially around the anchor points. This may reflect a different compaction energy introduced around these points, which creates a distinctive structure in the surface of the concrete: The smooth whitish film that is found on the rest of the surface is missing above the anchor points. Here, different conditions are present during the surface drying process for the precipitation of calcium hydroxide or calcium carbonate [7]: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$. Results are currently under closer analysis. Despite these observations, the findings show that it is possible to produce 20-24cm thick concrete walls that can support a 5 to 6 story building, whilst having the performance characteristics of a Passivhaus. The small outer shell specimens show that it is possible, with just a little extra effort but without a levelling layer, to

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produce high quality concrete surfaces that will be accepted by both clients and users. The full-scale samples require further optimization.

4 DISCUSSION

From an ecological balance perspective concrete performs badly, but it has good characteristics in terms of load-bearing ability, fire protection and soundproofing. As a result of its poor ecological footprint, one possible approach would be to reject concrete as a building material as a matter of principle, and to research and develop alternative materials with similar properties. The disadvantage here is that reliable results may only become available years into the future. In order to make a positive contribution to the “energy revolution”, this research project consciously follows the path of optimization of the existing: Because of the broad field of application and wide usage, an effective contribution can still be achieved.

5 CONCLUSIONS

The cause of the colour and mix differences around the horizontal anchor penetration points must be determined; this should then point to a remedy. The integration of the wall system in a coherent prefabricated construction system for residential and office buildings of up to 6 storeys should take place in a further project. As part of which the fire performance must be investigated. The even distribution of the dispersals, e.g. crushed recyclate, on the horizontal formwork tables can be improved in further research with machines. The results confirm the optimization potential for prefabricated concrete wall elements with the proposed materials and production methods. In dense urban spaces with high land costs, both the slenderness and innovative surface appearance of the newly developed approximately 20cm thick load-bearing outer walls play a significant role. The speed of construction will be optimized in terms of prefabrication and installation on site. The use of performance materials and recyclates can contribute to sustainable building.

6 ACKNOWLEDGMENTS

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Captions: EBB stands for the professorship “Entwerfen, Baukonstruktion und Baustoffkunde“, Chair of Building Construction and Material Science, MB stands for “Massivbau”, chair of Concrete Structures.