Part 1: Material Selection and Mix Design

Specification of eco-efficient concrete for precast components

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Innovative concrete technology makes it possible to mitigate the environmental impacts – that is to say greenhouse gas emissions (Global Warming Potential, GWP) and the embodied grey energy (Total Primary Energy Requirement, TPER) – of concrete, the construction material most utilised throughout the world. So-called "eco-concretes", or the binding agents with low Portland cement clinker content employed with such, generally exhibit slow strength development. However, producing precast components requires rapid strength development in order to attain short formwork stripping times. In addition, descriptive standards prescribe a minimum binding agent content and maximum water/binding agent value (w/b value) with the aim, amongst others, of safeguarding concrete durability that cannot be maintained with especially environmentally friendly concretes. The present paper will demonstrate in its first part how eco-efficient concretes can be designed utilising a concept of combined micro and "eco" fillers. These have less impact on the environment, good production-friendly processability and great early strength when compared with traditional concrete for precast components. Examples of prototypes from Austria will be presented.

In these times of climate change, it is worthwhile utilising resources sustainably and rendering concrete – the well-proven and most utilised construction material in the world – more environmentally friendly. In a recently completed research project at Graz University of Technology together with the Austrian Association of Concrete and Precast Manufacturers and seven precast component producers from Austria, it was demonstrated how the composition of concrete for structural precast components can be improved in such a way that its global warming potential, GWP or kg CO_2-equ. and its consumption of resources (total primary energy requirement TPER) can be substantially reduced in comparison with conventional standard concrete. All specifications as regards production-friendly processability and good early strength were fulfilled. All requirements concerning facing concrete quality, durability and cost-effectiveness were fully respected. The principle of performance based design specifications was systematically applied in the project to typical sorts of concrete for structural precast components. Construction component prototypes made from eco-efficient concrete were manufactured in several Austrian precast component production facilities and their concrete properties compared with construction components made from standard concrete. Part 1 of this paper at hand describes the principles of material selection, concrete development, the assessment of functional properties and the impacts on the environment. In particular, it will be demonstrated how, despite reduced Portland cement clinker content, good processability and great early strength were obtained with reduced impacts on the environment - which means an increase in "eco-efficiency".

Eco-filler/ micro-filler concept

The principles of "green" or "ecological" concrete have been outlined in [1-6]. Cement clinker is mainly responsible for the GWP and TPER of concrete [1], [2]. It forms the main component of common CEM 1 Portland cement and also of CEM II/A Portland composition cements (hereafter designated as CEM). These types of cement are usually employed in concrete for structural precast components. This study's general approach is illustrated in Figure 1 according to [7-9]. The methodology is based on optimising packing density and the water requirement of the binding agent and all substances in powder form (i.e. all granular substances with a maximum particle size of < 125 µm) – in short "powders" – in concrete, whilst at the same time taking the impacts of these substances on the environment into account. The approach goes beyond a simple utilisation of any composite cements available. Their utilisation may initially seem to be advantageous as regards an improvement in impacts on the environment but does not meet all requirements placed on concrete for precast components. An "eco-concrete" must attain minimum equivalent performance in respect of processability, (early) strength and durability when compared with normal concrete according to the current valid descriptive standard for precast concrete components. In optimised binding agent matrices, cement clinker with its high GWP and TPER is partially replaced by carefully selected very fine micro-fillers (MF) and coarser eco-fillers (EF), which exhibit less need of water and lower environmental stresses than CEM (Table 1). As is known from stud-

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ies about ecological concrete [6] and ultra high performance concrete (UHPC) [10], enhanced packing density is attained by a physical filler, if the MF possess a size ratio to the larger particles (e.g. cement particles) of $d_{MF} / d_{CEM} \leq 0.33$ with an optimum at $d_{MF} / d_{CEM} \leq 0.1$. Practically speaking, MF should in any case exhibit an average particle diameter $d_{50} << 5$ µm, i.e. be considerably smaller than CEM. In this study MF and EF are mostly carefully selected powdered limestone (CAL) and ground granulated blast furnace slag, (GGBFS). Other fines possible in eco-optimisation are dolomite rock flours, quartz powders, calcinated clays and other secondary substances, such as filter dusts and fly ash (FA), if available. GGBFS, calcinated clays and FA have a latent-hydraulic or pozzolanic action and thus contribute to strength formation at a later concrete age (from some days after the concrete is manufactured). They generate a dense concrete microstructure and have a positive action on the concrete's chloride and chemical resistance.

An optimised mixture made from CEM/EF/MF according to Figure 1 requires less water for a specific flowability than normal binding agent paste (mainly out of CEM). This is on account of the following factors: (i) packing density optimisation due to the physical filling action of MF or an optimised particle size distribution of all granular substances; (ii) a significant amount of EF, which exhibit great sensitivity to additions of water and thus lessen the need of water for a specific flowability of a mix; (iii) the addition of highly effective superplasticisers (SP). As SP, mostly of a PCE type (polycarboxylate ether), exhibit considerable environmental pollution (Table 1), they have to be employed sparingly in an optimisation process. A mix with optimised

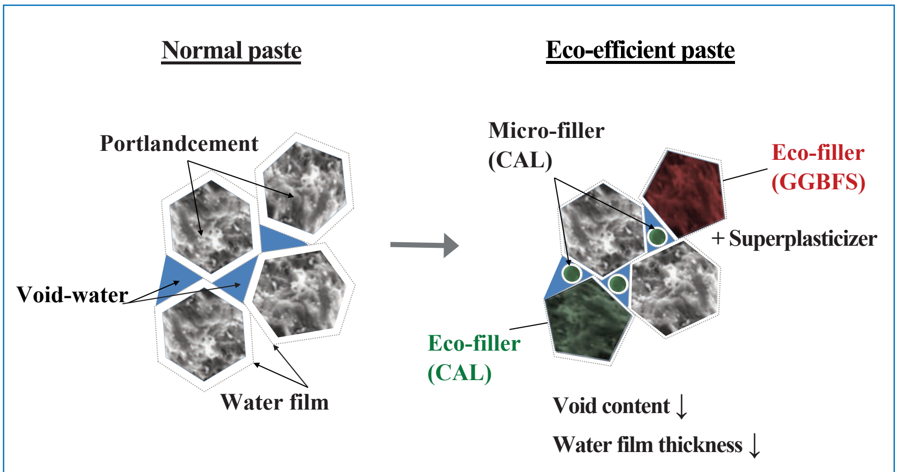

Fig. 1: Packing density optimisation and reduction of water requirements through the combined substances of a fines paste

packing density makes it possible to lower the total amount of water in a mix and its w/b value (water/binding agent value). This generally leads to great strengths. In our case with eco-concrete, the mix becomes more eco-efficient, in that CEM or clinker is partially substituted by environmentally friendly MF and EF. Such eco-mixes typically have a lower total amount of water but the same or even higher w/b value than normal cement paste. In binding agent b, CEM as well as GGBFS are allowed for in equal measure, whereas with rock flours, such as the limestone powders utilised in this case, no hydraulic activity is allowed for. Eco-mixes possess greater packing densities and a lower w/p values (water / powder value) with an equivalent flowability and at least the same (early) strength as standard mixes.

Material selection according to environmental impact

All source materials used were assessed using the life cycle assessment method as to their GWP and TPER according to ISO 14044:2006 with the aid of software (SimaPro, v.7.3) and the Ecoinvent database (Ecoinvent v2.2.). The results are given in Table 1 and Figure 1. Rock flours and secondary raw materials (such as GGBFS) that had been prepared by grinding were classified as regards their fineness as MF and EF made from limestone powder (CAL). As a rule, increasing fineness and hardness as well as the repeated screening of substances is accompanied by an exponential increase in energy requirements and a concomitantly raised environmental impact [11]. The action of fineness (grinding, screening) on GWP and TPER was quantified on the basis of information from several manufacturers of rock flours and evaluated in comparison with the cements investigated (CEM I 52.5 R and CEM II/A-S 52.5 N according to EN 197-1). There is a difference in the environmental impacts GWP and TPER of EF-CAL and MF-CAL. It is nonetheless evident that the GWP and TPER of both types of cement are substantially greater than that of aggregates, secondary raw materials and rock flours (EF-CAL, MF-CAL). Pure Portland cement CEM I exhibits greater GWP and TPER values than CEM II/A-S Portland composite cement with an up to 15% proportion of GGBFS as additive. The environmental impacts of the superplasticiser (PCE), which has high primary energy requirements in production and thus also great GWP and TPER, must also be taken into account. They were extracted from [12]; [13] gives still higher values.

Material selection according to chemical-physical criteria

In selecting materials with potential for optimising eco-efficiency, knowledge has first to be gained about their fineness (i.e. specific surface measured according to BLAINE and average particle diameter d_{50}), particle size distribution (measured using laser diffractometry) and their (single substance) packing density Φ_{exp}. Another crucial factor is the water requirement for the targeted flowability (parameters $V_{wf,100}/V_p$ and E_p) of a substance, a parameter of potential processability. On top of this, consideration has to be given to the interaction between particles in the substance and the degree of compaction attained in the mixing process [5], [14]. In the paper at hand, a new combination of methods was employed to develop (i) powdered substances experimentally in terms of Φ_{exp} and $V_{wf,100}/V_p$ as well as to characterise E_p and (ii) systematically optimised water / powder mixes made from CEM,

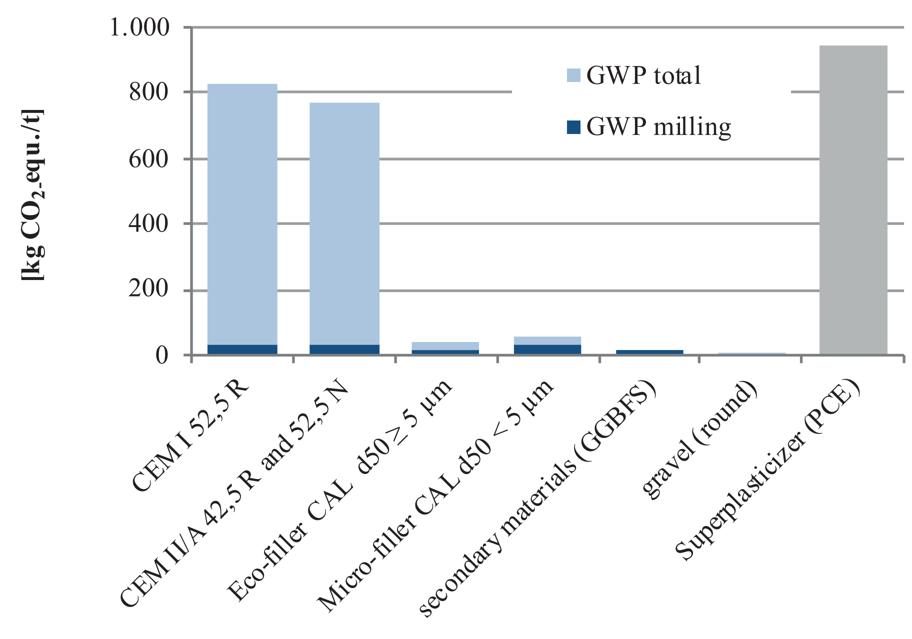

Fig. 2: Total GWP of potential source materials for concrete and the proportion arising from their grinding and screening

Table 1: Source Material Properties

Type	True density	Average particle diameter	Blaine value	Packing density	Water need flow start	Sensitivity water addition	CO_2 equivalent	Primary energy requirement
	ρ_0 [g/cm³]	d_{50} [µm]	[cm²/g]	Φ_{exp} [-]	V_{w100}/V_p [-]	E_p [-]	GWP [kg CO_2-equ./kg]	TPER [MJ/kg]
CEM I 52,5 R	3.14	6.3	5036	0.525	1.25	0.22	810	4030
CEM II/A-S 52,5 N	3.20	7.0	4097	0.548	1.31	0.19	769	3786
EF-GGBFS	2.89	9.2	4064	0.515	1.07	0.05	17	486
EF-CAL	2.70	9.0	3520	0.632	0.82	0.06	25	717
MF-CAL	2.70	2.2	10652*	0.554	1.30	0.11	35	1005
Sand 0/4	2.73	949	Measurement not possible				2.4	58
Gravel 4/8	2.73	4556					2.4	58
Gravel 8/16	2.65	7813					2.4	58
Superplasticiser (PCE)	1.06	Measurement not possible					944	29150

* Blaine values > 5500 are outside of the measurable area and are here only to be understood as guide values.

EF and MF. The procedures are described in detail in [9], [17]. In the first part of the procedure combination, the maximum attainable packing density Φ_{exp} of the water / powder mix was determined according to Marquardt [15]. To this end, the maximum power consumption (that required by the mixer at a constant rotational speed during a continuous addition of water) was measured whilst mixing a powder. The point of maximum power consumption corresponds to the water saturation point or the minimum cavity water content (this gives Φ_{exp}). In the second part, a spread flow test according Okamura [16]) was carried out. This enables the quantity of water to be determined that is just sufficient to cause a water / powder mix to flow under its own weight ($V_{wf,100}/ V_p$) and, beyond this, to determine the sensitivity of the mix in relation to further additions of water in stages, characterised by parameter E_p. In our case, no FM was utilised throughout the entire procedure. The properties of the substances utilised in this paper are listed in Table 1.

Packing density optimisation and reducing water requirements by using fines pastes

Regionally available fines with a suitable particle size and the least water requirement possible (low$V_{wf,100}/V_p$ andE_p) plus low GWP and TPER were selected from a number of characterised materials (CEM, EF, MF). Alongside powdered limestone, GGBFS was utilised as EF in order to meet enhanced specifications concerning durability. An optimum mix ratio of CEM:EF:MF was able to be found in which the method combination described above was employed in series of tests with successive variations in quantity fractions. The objective was to find a mix with minimum water requirements for a defined flowability with the greatest substitution possible of CEM by environmentally friendly fillers but that still exhibited sufficient strengths. With a view to assessing the targeted strengths (i.e. sufficient formwork stripping strengths after < 24 h and nominal strengths after 28 days), prisms were made from the mixes with a defined flowability (spread flow test according to Okamura of 160 mm), whose strengths were tested according to EN 196-1.Optimum mix ratios with a maximum packing density were computed in advance with the aid of a compaction interaction model (CIPM) according to Fennis-Huijben [5], in order to keep experimental complexity as low as possible.

Eco-efficient concretes with great early strength

The concretes' mix design

All eco-concretes were developed from optimised fines compositions (CEM:EF:MF), silicate aggregates and PCE superplasticisers with the requirement that they be at least equivalent (equivalent concrete performance concept, ECPC) to a reference concrete according to the current valid standard (ÖNORM B 4710-1:2018 and EN 206-1:2014) in respect of processability, early strength and normative 28 d strength, plus durability (see Part 2 of the paper). For this paper at hand, two reference concretes were chosen that correspond to typical mix compositions from Austrian manufacturers of structural precast components for applications in outdoor areas, see Table 2. Their concrete type designation with the provision of 28 d strength and exposure class covered by the standard is C 30/37 XC4/XW1/XD2/XF1 GK16. The reference concretes – CEM I 52.5 R und CEM II/A-S 52.5 N – were manufactured with two different types of cement and the same w/b value (w/b = 0.53 = maximum approved value according to standard). CEM I 52.5 R is a pure Portland cement with high reactivity and rapid early strength development, whilst CEM II/A-S 52.5 N with GGBFS as an additive exhibits somewhat slower early strength development. The eco-concretes developed (E-GGBFS and E-CAL) were designed with 2 different fines compositions and systematically varied w/b values (0.53; 0.56; 0.59), see Table 2. Whereas E-GGBFS contains CEM I in combination with two limestone powders EF-CAL and MF-CAL plus GGBFS, the E-CAL mix is only composed of CEM I and the two limestone powders. It must be noted that the eco-concretes exhibit a greater packing density or lower w/p value than the reference concretes, whilst their w/b value is the same as or greater than that of the reference concretes. The w/b value of the eco-concretes thus in part exceeds the maximum approved w/b (= 0,53) value for the above exposure classes given in standard ÖNORM B 4710:2018 according to the descriptive approach. Their cement content or clinker content is, in addition, substantially less than that of the reference concretes and is under the minimum binding agent content in the standard (in this case 315 kg/m³).

The same silicate aggregates with a 16 mm largest grain size were utilised for all concretes. The particle size distribution was adapted to Fuller's parabola to lie close to B in the grading curve area according to standard ÖNORM B 4710-10:2007. The aim was to have a very soft class F 52 consistency (with a flow spread of 52±3 cm on the flow table according to EN 12350-5:2009) ten minutes after ending mixing. To attain this with eco-concretes, the superplasticiser dosage had to be slightly increased in relation to the reference concrete. The paste volume was kept constant in order to ensure direct comparability of the fines composition in terms of strength and durability test results. A superplasticiser mix made from 2 products containing PCE was utilised in a ratio of 1:1. According to information from the manufacturers, SP1 has a strong liquefying effect, whereas SP2 offers good consistency behaviour. Superplasticisers were used as sparingly as possible on account their significant impact on the environment.

Comparison of the concretes' performance

The performance of the concretes was investigated in respect of processability, compressive strength, and durability (see Part 2 of this paper) as well as in relation to environmental impacts. The flow spread (according to EN 12350-5:2009) was tested ten minutes after adding water 10 min (A10) and again 30 minutes (A30) afterwards. Computations were made with the ratio A30/A10 in order to assess whether the consistency could be maintained for a sufficiently long time in a produc-

Table 2: Composition of the concretes

	Unit	R-CEM_II	R-CEM_I	E-0,59_ GGBFS	E-0,56_ GGBFS	E-0,53_ GGBFS	E-0,59_ CAL	E-0,56_ CAL	E-0,53_ CAL
CEM:EF-GGBFS: EF-CAL:MF-CAL	M.%	100:0:0:0	100:0:0:0	64:13:16:7	64:13:16:7	64:0:29:7	64:0:29:7	64:0:29:7	64:0:29:7
CEM II/A-S 52,5 N	kg/m³	330.0	–	–	–	–	–	–	–
CEM I 52,5 R		–	330.2	235.6	241.0	250.4	251.1	258.2	267.8
EF GGBFS		–	–	49.8	50.9	52.9	–	–	–
EF CAL		–	–	58.1	59.4	61.8	111.5	114.6	118.9
MF CAL		–	–	26.7	27.3	28.4	26.5	27.3	28.3
Sand 0-4 mm		763.2	760.6	745.9	746.4	744.4	757.4	757.5	756.1
Gravel 4-8 mm		361.1	359.9	363.1	363.3	362.3	368.6	368.7	368.0
Gravel 8-16 mm		756.2	753.6	734.0	734.5	732.5	745.3	745.4	744.1
Total Water		174.4	174.9	168.5	164.2	160.9	148.7	144.5	141.4
SP1 (PCE)		1.5	1.3	1.2	1.6	1.7	2.2	2.6	3.7
Paste volume	l/m³	289	294	294	292	292	292	292	294
w/b (b = CEM+GGBFS)	–	0.53	0.53	0,59	0.56	0.53	0.59	0.56	0.53
w/c (c = CEM)		0.53	0.53	0.72	0.68	0.64	0.59	0.56	0.53
w/c volumetric		1.69	1.66	2.25	2.14	2.02	1.86	1.76	1.66
w/b volumetric		1.69	1.66	1.83	1.74	1.64	1.86	1.76	1.66
w/p volumetric (p = CEM+GGBFS+EF-CAL+MF-CAL)		1.69	1.66	1.37	1.30	1.22	1.13	1.07	1.01

tion process. Its 24 h early strength and 28 d compressive strength fcm,28d was tested on concrete cubes (150 mm, n = 3) according to EN 12390-3:2009. After demoulding (24 h after being produced), the cubes were stored under water up to age of seven days and then up to 28 d at 65% relative moisture and 20°C.

The GWP and TPER environmental impacts of the reference and eco-concretes were determined on the basis of the life cycle assessment indicators of their source materials as is given in Table 1. To this end, the environmental impacts of the quantities of individual substances were added up for each m³ of fresh concrete. The impact on the environment occasioned in producing concrete, such as energy consumption, for example, was assumed to be equally great for both reference and eco concretes since they were manufactured in a precast component production facility with the same methods. This means that they are not relevant for the relative comparison of reference and eco concretes here.

Table 3 lists the results of tests concerning fresh and hardened concrete properties as well as the environmental indicators computed for them. Each of these performance parameters for eco-concretes can be compared with the relevant R-CEM I and R-CEM II reference value corresponding to the ECPC. For a better comparison, the R CEM II reference concrete's values were standardised (100%) and the parameters of the eco-concretes placed in relation to them. In the comparison with R CEM I, it can also be seen what impacts just changing the cement can cause. Figure 3 shows its processability (flow spread A10), consistency behaviour, the 24 h ($f_{cm,24\,h}$) and 28 d compressive strength ($f_{cm,28\,d}$) as well as GWP, TPER.

The objective of improving the life cycle assessment performance (less GWP and TPER) whilst keeping processability as well as early and hardened strength at the level of the reference concretes, was attained or even exceeded with all variants. The eco-efficiency of the concretes was enhanced. GWP was reduced by up to 30% and TPER by up to 14%. It was not possible to reduce TPER by the same amount as GWP since the greater dosages of superplasticiser with the eco-concretes in comparison with the reference concretes have a greater action on the TPER values than on those of the GWP.

Certain properties of the concretes, such as processability and early strength (and durability as well, see Part 2), were able to be influenced in a targeted way with the EF/MF concept. At least as equally high 24 h strength ($f_{cm,24\,h}$) with the eco-concretes was able to be achieved as with the corresponding reference concretes with similar processability through selecting suitable very fine micro-fillers and the reduced c/p value. This

Table 3: Concrete properties

Parameter	Unit	R-CEM_II	R-CEM_I	E-0,59_ GGBFS	E-0,56_ GGBFS	E-0,53_ GGBFS	E-0,59_ CAL	E-0,56_ CAL	E-0,53_ CAL
Flow Spread A10	cm	48.0	52.5	51.0	50.0	60.0	53.5	56.0	49.0
A30/A10 Consistency behaviour	-	1.00	0.97	1.04	0.98	0.85	0.91	0.85	-
$f_{cm,24h}$	N/mm²	18.5	28.3	18.8	21.1	25.4	33.1	36.6	42.1
$f_{cm,28d}$	N/mm²	54.2	61.7	56.2	58.6	67.7	67.3	69.0	85.9
GWP	kg CO_2-equ./m³	259.7	273.2	199.7	204.8	212.3	212.5	218.7	228.5
TPER	MJ/m³	1401.9	1476.5	1184.1	1232.7	1264.5	1257.6	1301.1	1407.0

was achieved despite the reduction in clinker and increasing the w/b value (to (w/b = 0.59) in comparison with the reference concretes (w/b=0.53). Even considerably greater early strengths could be obtained with those eco-concrete mixes, which exhibited a lower w/b value (0.56 or 0.53) than the corresponding reference concretes. However, the GWP and TPER environmental impacts increase with growing FM content and consistency behaviour decreases.

Manufacturing prototypes and outlook

In the course of this project, precast component elements for outer walls were produced from eco-concrete and installed in an outbuilding alongside the same made from C 30/37 XC4/XW1/XD2/XF1 GK16 standard concrete on the grounds of Graz University of Technology (Figure 4, Figure 5, Figure 6).

It was a successful demonstration of the fact that eco-concrete for precast components is also equivalent to a standard concrete in normal production runs in terms of its processability and early strength in a precast component factory, whilst exhibiting up to 30% less GWP and up to 14% less primary energy requirements than standard concrete according to the current standard.

Since its environmental impacts were substantially reduced, it is perhaps better to speak of an “Improved concrete performance concept” than an “Equivalent concrete performance concept” (ECPC)!

Finally, it should be noted that cost (estimations) of eco-efficient concretes show that the cost/m³ concrete – with the exception of investment that perhaps may occur for additional storage or silo capacities – are somewhat lower or at most

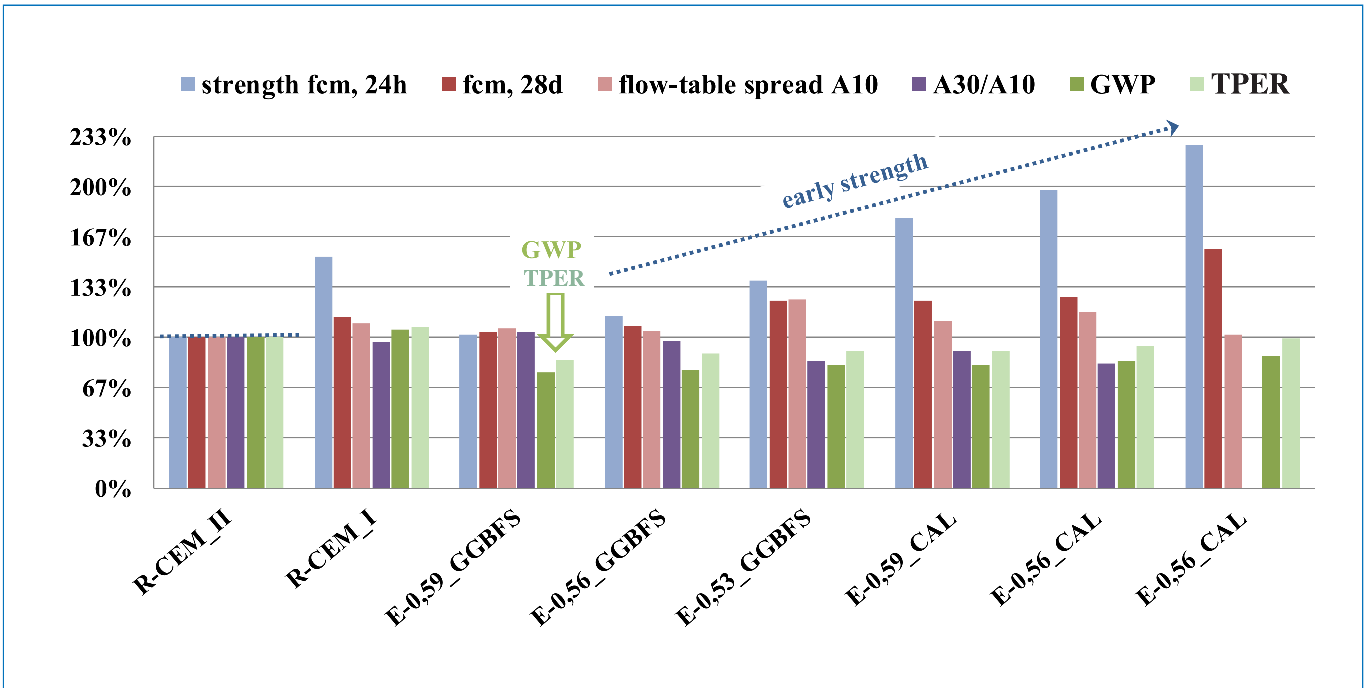

Fig. 3: Performance in relation to strength, consistency, GWP, TPER

Fig. 4: Producing an outer wall element from eco-concrete

Fig. 5: Displacing an outer wall element made from eco-concrete

equally high as for standard concrete. Future costs will be especially determined by price developments for MF and EF plus SP.

The second part of this paper will deal with the stability and durability of eco-concretes in comparison with reference concretes according to the descriptive standard. Using concretes for precast components for structural outdoor construction components, it will be shown how the stability for exposure classes stipulated according to standard in line with the equivalent concrete performance concept (ECPC) was verified in an extensive test programme. Parameters for eco-efficiency concerning precast component applications will also be stated.

Fig. 6: Detail of an outer wall element made from eco-concrete in facing concrete quality

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