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Experimental and Theoretical Study of Earth-Moist Concrete

Introduction

Earth-moist concrete mixes are the starting substance for the mass production of concrete products like pipes, slabs, pavement stones and curb stones. The working properties of earth-moist concrete (EMC), caused by its dry consistency, are advantageous. So, in comparison to normal-weight concrete, the consistency of EMC allows for direct stripping of concrete products after filling and vibrating the molds. As a result, short processing times of the production process can be realized. Further examples for concrete with stiff consistency are roller compacted concrete (RCC) which is stiff enough to be compacted by vibratory rollers. RCC is used for any type of industrial as well as heavy-duty pavements or in combination with bigger aggregates as roller compacted concrete for dams (RCD).

Traditional earth-moist concrete mixes for concrete products are characterized by high cement contents between 350 kg and 400 kg per m^3 concrete and a low content of fine inert particles. They have a low water/cement ratio ($w/c < 0.4$) combined with a very stiff consistency and a high degree of compactibility. Furthermore, the degree of consistency of EMC is defined by Häring as free-flowing /5/. As a result of low water/cement ratio, high compressive strength values are achieved by earth-moist concrete mixes and durability is improved compared to ordinary concrete. However, despite these positive properties there is potential for improvements. Possible fields for improvements are in the workability, compactibility, green strength, packing density and a reduction of the cement content by using fly ash, limestone powder or other possible powders as a substituent, such as fine stone waste products, in order to increase the content of fine inert particles. This replacement of primary raw materials by secondary waste materials constitutes an environmental and financial advantage.

An optimization of the packing and the ratio of water in voids, in consideration of the material properties of the available raw materials, can lead to an increase in the green strength of fresh concrete and to higher compressive strength values of the concrete in hardened state. With an increase in compressive strength, the amount of cost-intensive cement can be reduced by using cost-saving powders as substituent. These powders, such as fly ash, will also influence the compressive strength of the hardened concrete positively. This enormous potential for optimization will be the starting point for further investigations into the development of EMC for the innovative production of concrete. At first, the packing of all aggregates will be investigated as an optimum packing is the key for a good and durable concrete.

Requirements on the packing in earth-moist concrete

To control the most important properties of EMC, like workability and strength, the optimum packing of all aggregates is of vital importance to reduce the amount or even to avoid the use of required admixtures. According to Brouwers and Radix /3/, the grading of all solid particles in the mix (gravel, sand, filler and cement) shall be considered integrally. Some general rules are already known from the mix design of self-compacting concrete (SCC) as well as conventional vibrated concrete (CVC). These rules are related to the packing of the solids and the granulometric properties of the raw materials.

The content of fine particles (paste) in SCC is much higher than in other types of concrete (see Fig. 1) in order to achieve a flowing and stable SCC /3/,/7/,/8/. In SCC, a high content of fine particle is required to reduce the internal stress as the energy for flowing is consumed by the internal stress. The internal stress increases as the relative distance between particles decreases and the frequency of collisions and contacts increases. The energy consumption of coarse aggregates is particularly intensive. So, the internal stress can be reduced by spreading out the coarse aggregates in SCC.

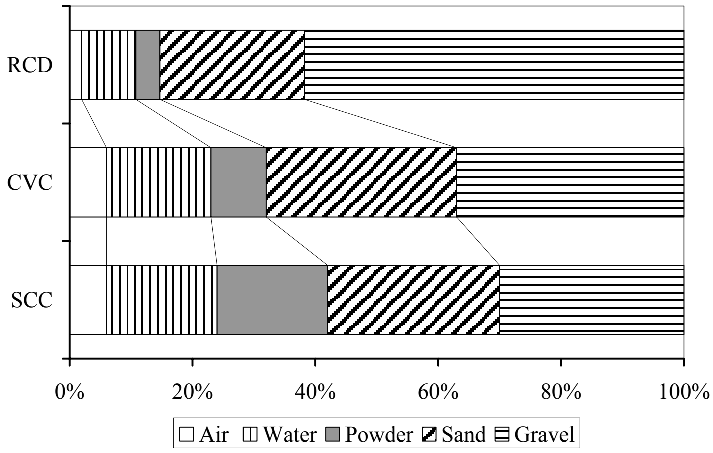

Fig. 1:

Comparison of mix proportioning for different concrete types /8/

The application of too high contents of fine materials in EMC hinders the achievement of densest packing together with high green strength values. For designing EMC, two opposite effects have to be considered.

First, the apparent cohesion will be influenced positively by increasing the content of fine materials as well as their fineness. Secondly, the inner friction will be reduced by spreading out the coarser grains by reducing the grain-to-grain contacts. Because the green strength is a result of the interaction of apparent cohesion as well as inner friction also the green strength is reduced.

Furthermore, the ratio between coarse and fine aggregates is vital in attaining high packing densities and small, with paste fillable, pore space /1/-/3/. Widely spread particle size distributions (PSDs) lead to a better packing than narrow graded aggregates. Thus it appears that the grading of all solids has to be considered in the mix design of EMC.

Mix design

For proportioning of the first tested trial mixes a first step to a new mix design concept was made. The aim of this new mix design concept is to design a concrete mix based on performance related requirements. Within this new concept the requirements on the designed concrete shall be determined by the required performance properties of the concrete and not by abstruse regulations of standards. This is realized by the formulation of an optimization problem using the modified equation of Andreasen and

Andersen (Equation (1)). This equation was modified by Funk and Dinger /4/ and prescribes the grading for continuously graded aggregates considering the minimum and maximum particle size in the mix. The positive influence of the modified A&A equation on the properties of self-compacting concrete was already shown by Brouwers and Radix /3/.

$$P_t(D_i) = \frac{D_i^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \qquad \forall D_i \in [D_{\min}, D_{\max}] \tag{1}$$

The formulation of an optimization problem requires three parts. These parts are:

- Target value
- Adjustable values
- Constraints.

Target value:

The target value represents the objective or goal of the optimization problem. This value shall either be minimized or maximized. In the considered case, the deviation between the desired grading of a mixture and the actually achieved grading of the mix shall be minimized. That means practically for the mix design of concrete that the difference (residual) in the grading between the given target function $P_t(D_i)$ and the function of the mixture $P_m(D_i)$ shall be reach a minimum value and results, in other words, in a curve fitting problem. To solve this curve fitting problem, the least squares technique is commonly used. Thereby, the sum of the squares of the residuals (*RSS*) is minimized. Equation (2) expresses the least squares technique mathematically.

$$RSS := \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} \left(P_m(D_i) - P_t(D_i)\right)^2 \rightarrow \min! \tag{2}$$

In order to evaluate the quality of the curve fit, the coefficient of determination R^2 according to Equation (3) is useful. It expresses the proportion of fluctuation between the target line and the obtained values for the grading of the composed mixture.

$$R^2 := 1 - \frac{\sum_{i=1}^{n} \left(P_m(D_i) - P_t(D_i)\right)}{\sum_{i=1}^{n} \left(P_m(D_i) - \overline{P_m}\right)} \qquad \forall D_i \in [D_{\min}, D_{\max}] \tag{3}$$

$$\text{with } \overline{P_m} = \frac{1}{n} \sum_{i=1}^{n} P_m(D_i)$$

Adjustable values:

Adjustable values are used by the optimization algorithm to approach the target value. These are the volumetric proportion ($v_{agg,k}$) of each raw material as well as the total amount of solids (V_{agg}) in the considered case. The volumetric proportion of each raw material influences the grading of the composed mix via:

$$Q_m(D_i) = \frac{\sum_{k=1}^{m} \frac{v_{agg,k}}{\rho_{agg,k}} Q_{agg,k}(D_i)}{\sum_{i=1}^{n} \sum_{k=1}^{m} \frac{v_{agg,k}}{\rho_{agg,k}} Q_{agg,k}(D_i)} * 100 \tag{4}$$

$$P_m(D_i) = \begin{cases} 100 & \text{for } i = 1 \\ P_m(D_{i-1}) - Q_m(D_i) & \text{for } i = 2...n \end{cases} \tag{5}$$

with $Q_{agg,k}(D_i)$: sieve residue aggregate k on sieve i;
$\rho_{agg,k}$: specific density of aggregate k

Furthermore, the volumetric amount of aggregates (V_{agg}) per m^3 concrete is changed by the optimization algorithm. The volumetric amount of aggregates per m^3 concrete is not connected directly with the target value. A connection exists here via the constraints.

Constraints:

Constraints are restrictions which are connected with the adjustable values and reflect real-world limits or boundary conditions. The formulation of the considered optimization problem distinguishes between physical constraints and policy constraints. The following constraints are defined to characterize the boundary conditions of the mix design:

- *Non-negativity constraint*: A negative volumetric proportion ($v_{agg,k}$) of each raw material as well as a negative volumetric amount of aggregates (V_{agg}) per m^3 concrete is no admissible solution.
- *Volumetric constraint*: The volumetric constraint takes into account that the sum of the volumetric proportion ($\Sigma v_{agg,k}$) of the raw materials cannot be higher or lower than 100 %. Moreover, the volume of all ingredients per m^3 concrete, according to Equation (6), cannot be higher or lower than 1 m^3.

$$V_{agg} + V_{cement} + V_{water} + V_{additives} + V_{admixtues} + V_{air} = 1\,\mathrm{m}^3 \tag{6}$$

- *Policy constraints*: These kinds of constraints represent requirements given by standards or particular requirements on the designed concrete like:

- Minimum cement ratio $V_{cement,min}$
- Maximum cement ratio $V_{cement,max}$
- Water cement/ratio w/c (will be replaced by w/f_{125} ratio in the future)

The optimization problem can be formulated when all constraints and requirements on the designed concrete mix as well as the material properties are known. For solving the optimization problem, an optimization algorithm was programmed in *Microsoft Excel 2003* using the embedded *Excel Solver Tool* as well as *Visual Basic for Applications*.

The volumetric content of the aggregates V_{agg} as well as the volumetric content of the additives V_{add} in Equation (6) is found out by the solution of the optimization problem. The solution of the optimization problem leads to a PSD of the composed solid mix which follows the given target function with a minimum deviation.

Concrete experiments

To investigate the influence of various target curves on the concrete properties, the degree of compactibility, the packing density and the compressive strength for various distribution moduli (*q*) of the modified A&A curve were tested combined with different water/cement ratios. The distribution modulus of the modified A&A curve was investigated for values of 0.25, 0.30, 0.35 as well as 0.40. A maximum particle diameter (D_{max}) of 16 mm and a minimum particle diameter (D_{min}) of 0.5 µm, based on the data obtained from particle size analysis were used. The maximum particle diameter is given by the coarsest aggregate (gravel 4-16). The minimum particle diameter represents the smallest particle size in the mix (CEM III/B 42.5 N LH/HS). The designed mixes were tested regarding their degree of compactibility, packing density and compressive strength after 28 days storage underwater. Selected series with high compressive strength values were tested for tensile splitting strength.

Figure 2 shows the volumetric composition of some of the tested trial mixes (based on the mix design of a company) as well as the improved mixes using the optimization algorithm.

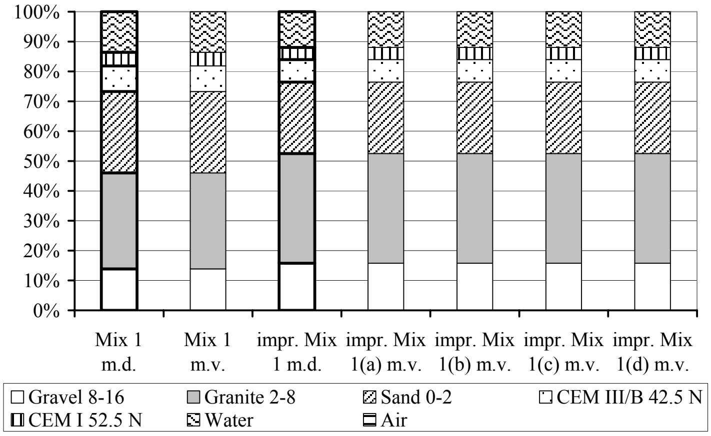

Fig. 2:

Volumetric composition of tested trial mixes (V/V);
m.d. - mix design
m.v. - computed values from measurements
a, b - mixes without plasticizer
c, d - mixes using plasticizer

A link between packing density and degree of compactibility is shown in Fig. 3. These tests were carried out to ascertain if test procedures using measurement of displacements, generated by means of compaction efforts, can be used for showing positive effects on the packing density. These kinds of test procedures are often used to evaluate EMC such as the modified Proctor test /2/ as well as the STEAG method /6/.

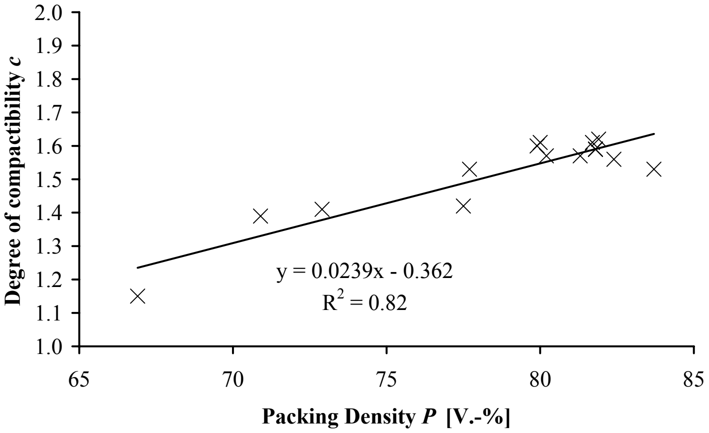

Fig. 3:

Degree of compactibility versus packing density

The positive effect of an improved and denser packing is shown in Figure 4. Here, the results for cement content of 310 kg CEM III/B 42,5N LH/HS per m^3 concrete and a blend of two different cements with 325 kg per m^3 concrete are compared. The blend consists of 65 % CEM III/B 42,5N LH/HS and 35 % CEM I 52,5N.

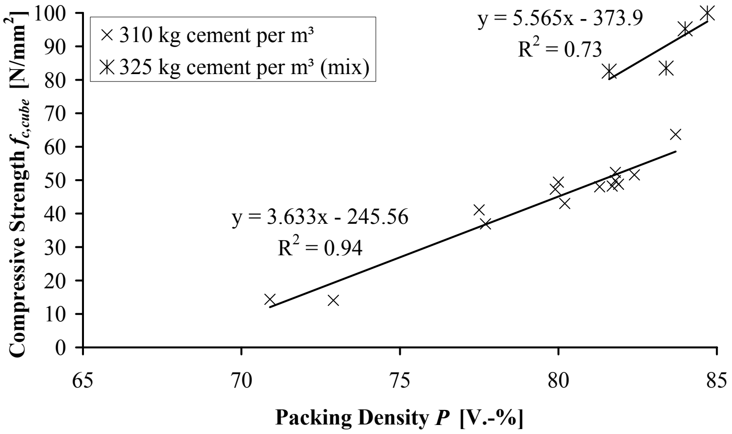

Fig. 4:

Compressive strength versus packing density

Packing densities between 70 % and 85 % can be achieved depending on the distribution moduli used. Mixes with low packing densities around 70 % are caused by mixes with paste content smaller than 0.2 m^3 per m^3 concrete combined with low *w/p* values of 0.30 or lower (the powder content is defined here as all particles with a size smaller than 125 µm, and they generally comprise cement, filler and the smallest fraction of the sand).

Distribution moduli between 0.25 and 0.30 show a form of gap grading effect in the range between 80 µm and 200 µm. The grading in this range follows the target function not as close as possible. For example, a distribution modulus of 0.25 requires a paste content of 0.38 m^3 per m^3 concrete which cannot be realized by the given cement content of 310 kg per m^3. Therefore, the difference between the grading of the mix and the target function is too big and the low paste content cannot meet the demands caused by the higher amount of sand in the mix.

Based on the obtained test results the following values are advisable for the mix design of EMC.

Distribution modulus (*q*): 0.35
Paste content (<125 μm): 0.225 – 0.250 m^3 per m^3 concrete
Water/powder ratio (<125 μm): 0.30 – 0.39
Water/cement ratio: 0.35 – 0.40 (used for the classical definition of EMC)

According to Figure 5, the distribution modulus of 0.35 results in a paste content of 0.257 m^3 per m^3 concrete for workable EMC mixes with *w/p* value of 0.35. The application of lower *w/p* values can be realized by means of plasticizers or other admixtures.

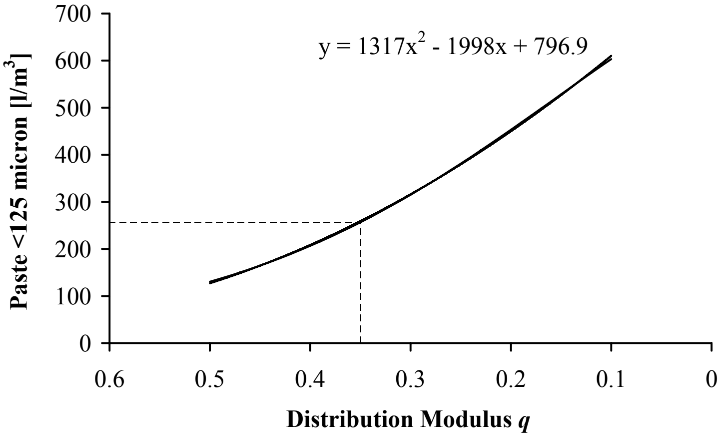

Fig. 5:

Calculated paste content (particles <125 μm and water) per m^3 concrete for a given water/powder ratio (*w/p*) of 0.35

The application of plasticizers showed already a positive effect on the packing density as well as the compressive strength (see Figure 5). Packing densities between 84 % and 85 % can be achieved by using paste content of 0.246 m^3 per m^3 concrete with *w/p* value of 0.33 and results in compressive strength between 95.7 N/mm^2 and 100.3 N/mm^2. These values are far in excess of the requirements given by Dutch standards. Also, the tensile splitting strength for this mix is with 4.9 N/mm^2 to 5.0 N/mm^2 higher than required by the European/Dutch standard NEN-EN 1338. The pertaining cement efficiencies are 0.294 and 0.309 N/mm^2 per kg/m^3, respectively, which is very high.

For tensile splitting strength, the NEN-EN 1338 prescribes a characteristic value for pavement stones higher than 3.6 N/mm^2 and an individual value higher than 2.9 N/mm^2. A further reduction of the cement content is therefore possible if a suitable material for replacement is available. For this purpose, a suitable material can be found in granite powder. This granite powder is a waste material accumulated during the washing of aggregates. The particle size distribution of the granite powder is comparable to cement and therefore this material will be applied in further investigations for replacing primary filler materials.

Furthermore, the first investigations on EMC showed that the w/c ratio is not applicable if the cement content is reduced. The reduction of the cement content will also reduce the water content in the mix if the w/c ratio is used for determining the amount of water in the mix. Mixes with low cement contents of 250 kg per m^3 concrete and higher contents of inert fines are resulting in very dry and not workable mixes if a w/c value of 0.40 is used. These mixes require the usage of cost intensive plasticizers or other viscosity modifying agents in big amounts. Therefore, the application of the w/c ratio or the limitation of this value is not appropriate for EMCs using low cement contents. Consequently, the paste content of the mix as well as the water/powder (*w/p*) ratio for particles smaller than 125 μm should be considered for EMCs. This new approach was already used by Bornemann /2/ for characterizing the ideal consistency range of EMC. Moreover, this approach results in a more performance based mix design of concrete.

Conclusions

The performed investigations on earth-moist concrete mixes confirm the fundamental idea of the new developed mix design. An improved and densest packing is the philosophy of this new approach. Using an optimum packing of all aggregates in the entire range (D_{max} till D_{min}), the properties of concrete in hardened as well as fresh state can be affected in a positive way.

At present, most attention was paid to concrete properties in hardened state as well as packing density. More attention will be paid on the durability behavior of the mixes in the future. But the optimization of the currently used mix from a company of the sponsor group showed already that the compressive strength of hardened concrete can be increased, whereby, at the same time, the cement content is decreased. A further decrease in the cement content can only be realized if a substituent material is available for the lacking part of cement. Otherwise, the improved granular structure is destroyed in this range of the particle size distribution. However, this range is important for the packing as well as the properties of hardened concrete because the processes in the area between aggregates and hardened cement paste determine the strength of the hardened concrete /9/.

In contrast to SCC, a distribution modulus of $q = 0.35$ turned out to be suitable for EMC. Here, the difference in the distribution modulus is anchored in the special requirements to both types of concrete. A workable SCC needs a high content of fines for self-flowing. Such a high content of fines cannot be applied in EMC. Using a too high content of fines in EMC, the water demand is increasing and the inner friction is decreasing in the same way. Also, the green strength is influenced in a negative way.

Based on the first results into the field of EMC presented here, future research will focus on the role of basic parameters such as the internal specific surface, packing efficiency, water/air content (saturation) etc on compactability, green strength, production speed and properties in hardened state. The objective is to design mixes that are cheaper and environmentally friendly and that meet all technical requirements.

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