Simple basic model for concrete and its application

Part 3. Factors affecting consistency, material balance equations and mix design

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Abstract

During the plant observations a number of interesting questions arose concerning consistency. The manufacturing plants (or the sites where pre-mixed concrete is transported from) are the ideal place for carrying out investigations to gather a wealth of valuable data. Nevertheless, the statistical characteristics for consistency in no way demonstrate the same kind of close correlation as those for compressive strength or deformation, so there is justification in being cautious, even though being cautious should never prevent us from drawing certain conclusions. When designing the composition of fresh concrete mixes, it may be useful to incorporate the (structural) content indicators of the concrete composition, provided that we know (or conduct experiments to find out) the correlations between the concrete composition content indicators and the properties of the fresh and hardened concrete, and apply the material balance equations of concrete mixes. The final part in this series of papers focuses on these issues.

1. A brief review of the literature

A knowledge of the factors that affect the consistency of fresh concrete is important for conscious planning of *workability*, and research has therefore long been conducted into this area. The work of *Alexanderson* is especially interesting because he has examined the different *composition* conditions under which constant consistency (consistency of the same class) can be provided, across a very *broad range* of mixes, from *paste* (mortar) *mixes* to *concrete mixes* [1]. The diagrams he published (see Figs. 27 and 28) express the principle that consistency could only remain constant when *dry* aggregates are added to a given cement paste of a known consistency if the water-cement ratio is simultaneously increased. The volumetric ratio of the aggregates in the concrete, however, can only be increased to a maximum limit, which also depends on consistency, roughly in line with Fig. 28. *Alexanderson* is remarkable in that he not only considers the *air content* of pastes (admixtures which form bubbles of air) and the impact they have on consistency, but he also calculates with it.

Fig. 27. Relationship between the percentage of aggregate by volume and the water/cement ratio at constant consistency, after *Alexanderson* [1]

27. ábra Az azonos konzisztencia biztosításához szükséges v/c tényező változása a betonban levő adalékanyag térfogatarányának függvényében, *Alexanderson* szerint [1]

Fig. 28. Aggregate limit value for concrete made with natural coarse aggregate and air content 1.5-2.5 V% (the Swedish designations for consistency classes are roughly in line with the scale of S1...S4 consistency classes)

28. ábra Az adalékanyag bedolgozható maximális térfogatarányának függése a finomsági modulustól, különböző konzisztencia-osztályok esetén (a svéd jelölések fentről lefelé nagyjából az S1...S4 osztályoknak felelnek meg)

In Hungary, the work of *Ujhelyi* in mix design accounting for consistency is outstanding: his DSc thesis of 1989 [2] not only gives a thorough summary of the methods for estimating water demands, but also describes a new method for calculating consistency-dependent water demands. The method is suitable for the design of consistency of mixes *without admixtures*. In the proposed formulae the water demands of aggregates depend on the *fineness modulus*, and the water demands of cement depend on the *specific surface area*. The latter predicts the so-called *surface aspect*: it is noticed that not only the masses and volumes of the set of solid phase components are included in concrete mixes, but also their *surface areas*, and the surface areas may have particular influences on the properties of the concrete.

Design of consistency is complicated due to the presence of cements and additions which have high specific surface areas and by the effects of high range water reducing admixtures - which can produce special rheological phenomena. This is the reason behind the ever increasing number of articles published in the last decade that deal with observations of the rheological behaviour of cementitious mixes. In Hungary, *Spráncz* and his associates have examined the *flow time* and *flow value* of pastes made by different

cements and admixtures, and have found numerical correlations between the rheological properties and the composition properties [3,4]. Their work was consciously directed towards the investigation of *pastes*, since (as *Alexanderson* also recognised) the rheological behaviour of concrete is determined to a great extent by the properties of the paste.

A source of inspiration for future research in Hungary could be provided by the report of *Toutou* and *Roussel* [5]. The authors examined the rheological behaviour of concrete constituents in *four cumulative stages*: firstly in *suspensions* (water + silica fume), secondly in *pastes* (water + silica fume + cement), thirdly in *mortars* (water + silica fume + cement + sand), and fourthly in *concretes* (water + silica fume + cement + sand + gravel). The rheological properties of all four types of mixes were investigated, and they reported interesting data concerning the correlations between *shear stress* and *shear rate*, and between *yield stress* and combined *volumetric ratios of solid phase constituents*. It would be worth pursuing this direction of research in Hungary too; it would not require unaffordable costs, but mainly systematic and perseverant work. The outcome would be more reliable mix design for concrete workability, particularly in the case of high performance concretes, which are more sensitive from a rheological point of view.

2. Factors influencing consistency according to the simple basic model for concrete

In the simple basic model, the influence of *concrete composition content indicators* is also a *subject for analysis* with regard to consistency and the rheological properties of fresh concrete (p : ratio of paste in the concrete, x : volumetric ratio of liquid to paste powder, χ_c : volumetric ratio of cement in the paste powder, λ_{AD} : volumetric ratio of admixtures to paste powder, l : volumetric ratio of air in the concrete), although the *physical properties of concrete constituents* must be considered at all times. For example, one such important influencing factor is the *volumetric specific surface area* of the *combined solid phase matter* (paste powder and aggregate particles) making up the concrete, which is calculated by the method described in [6]; which is essentially the procedure proposed by *Kausay* [7], with the difference that *as standard* the particles are considered to be not spherical, but ellipsoid in shape. The role of the surface area of materials included in concrete mixes is obvious, because during the flow of the concrete, the *combined solid particles* have a *mutual effect on each other through their surface areas*, and also have an effect on the fluid (*water*, which may also contain *admixtures*) that plays the role of dispersing agent.

Concrete is considered from a rheological point of view to be a self-affine (fractal-like) composite system, which manifests itself in the combined solid phase of constituents in dimensions of different scales *showing a repeating structure*. The *cement + addition powder as dispersed phase* plays the same role in *paste* as it is played by *aggregate in concrete*. Also, the *fluid* (mostly water), which is the *dispersing agent* in the paste plays the same role as it is played by the *paste in concrete*. *Paste* acts as the *dispersing agent* for the *aggregate* as the *dispersed phase*. The only substantial difference between the aforementioned dispersed phases lies in the 2 order of magnitude difference between their

particle sizes, but the structure in the different magnitude scales is *continuously* repeated, which can presumably be traced back to the *exponential distribution* of the particle sizes of the combined solid phase constituents of concrete.

If the surface of the powder particles of the paste are covered in a *thick layer* of fluid (but naturally not so thick that they can bleed) then the paste can be expected to flow better than if the layer of fluid covering the particles is *thinner*. The same large-scale range of dimensions is still valid: if the surface of the aggregate is covered by a *thick layer* of paste (acting almost as a fluid) then the fresh concrete mix can be expected to flow better than in the case where the aggregate gets a *thin layer* of paste. From the point of view of fluidity, *the consistency of the neat paste serves as the maximum threshold value* (in this case the *paste thickness* is infinite), since when combined solid phase matter is added to the paste (either aggregate or paste powder) then the added surplus surface area dilutes the thickness of the dispersing agent covering the dispersed particles, causing a decreased fluidity of the mix.

The influence of water-reducing admixtures ($\lambda_{AD} > 0$) – following the above idea – can also be interpreted as diluting the thicknesses of the dispersing agent which would be necessary to achieve a given consistency in mixes without admixtures *in every range of dimensions of the dispersed phase particles*. In the case of the 132 batches of plastic consistency concrete mixes investigated during the *plant observations* detailed in [8] (of which 72 were made without admixtures, and 60 were made by water-reducing admixture), the *average thickness* of the paste (as dispersing agent) reaching the aggregates within the range of dimensions $\varnothing 0.063$ –32 mm was, significantly, *several μm thinner* for mixes *with* admixtures than for mixes *without* admixtures. This paste diluting effect can actually represent savings in paste between 10 to 30 litres (depending on the type and characteristics of the aggregate) when applied to each cubic meter of mix.

If the mix composition of the concrete is known, then the *thickness* of a dispersing agent covering a d sized particle in the dispersed phase can be calculated simply by Eqs. (37) and (38):

$$t_a = \frac{1}{2} \cdot d_a \left(\left(1 + \frac{p}{a} \right)^{\frac{1}{3}} - 1 \right) \quad (37)$$

$$t_z = \frac{1}{2} \cdot d_z \left(\left(1 + x \right)^{\frac{1}{3}} - 1 \right) \quad (38)$$

where:

- t_a is the thickness [mm] of the layer of paste covering the aggregate particles of diameter d_a [mm],
- t_z is the thickness [μm] of the layer of fluid (water) covering the paste powder particles of diameter d_z [μm],
- p is the volumetric ratio of the paste in the concrete (concrete composition content indicator),
- a is the volumetric ratio of aggregate in the concrete ($a > 0$), and
- x is the volumetric ratio of fluid-paste powder.

		Concrete composition (structural) content indicators					Other technical data and information			
		p	x	χ_c	λ_{AD}	I	Admixtures included in the evaluation*	Traditional w/c ratio	a**	D _{max} mm
Plant observations of consistency 2008-2010. 242 observations	min	0.153	0.924	0.552	0.000	0.000	High range water reducer (HRWR)	0.335	0.652	4
	max	0.314	3.381	0.977	0.030	0.088	Mid range water reducer (MRWR) and	1.218	0.790	32
	average	0.255	1.684	0.839	0.009	0.017	3 types of water reducers (WR)	0.685	0.728	24
	distribution	0.021	0.301	0.080	0.009	0.014		0.143	0.019	8

Table 11. Concrete composition content indicators and other data for mixes subjected to consistency examinations during plant observations;

*Note: The product names of the admixtures have been omitted intentionally; **Note: a: the volumetric ratio of aggregate in the concrete mix

11. táblázat Az üzemi megfigyelések során konzisztencia-vizsgálatoknak alávetett keverékek betonösszetéti állapotjelzői és egyéb adatai (* az adalékszerkezetek termékmegnevezéseit szándékosan mellőzzük, ** a: a betonkeverékben lévő adalékanyag térfogataránya)

Admixture code name	Number of observations	p – paste volumetric ratio		x – fluid-powder volumetric ratio		λ^* - dose of admixture as volumetric ratio of the paste powder			Measured flow values [mm]		Factors for Eq. (39)	
		p _{min}	p _{max}	x _{min}	x _{max}	λ_{min}	$\lambda_{average}$	λ_{max}	flow _{min}	flow _{max}	f _{1,AD}	f _{2,AD}
without admixture	113	0.153	0.302	1.254	3.381	0.000	0	0	300	470	1	1
HRWR	49	0.220	0.267	1.287	1.675	0.010	0.014	0.025	390	550	14.256	1.004
MRWR	10	0.212	0.314	0.924	1.872	0.008	0.016	0.030	340	590	8.868	1.012
WR-1	28	0.214	0.285	1.076	1.975	0.012	0.020	0.029	380	480	4.529	1.012
WR-2	31	0.217	0.290	1.297	1.876	0.006	0.016	0.028	350	480	4.846	1.017
WR-3	11	0.240	0.263	1.215	1.850	0.012	0.020	0.028	390	480	4.042	1.004

Table 12. Data concerning the concrete composition content indicators and consistency values for mixes made with and without different types of admixture, and the factors $f_{1,AD}$ and $f_{2,AD}$ of Eq. (39)

12. táblázat Az adalékszer nélküli és a különböző adalékszerekkel megvalósult keverékek betonösszetéti állapotjelzőinek és konzisztencia mértékszámainak adatai, valamint a (39) képlet $f_{1,AD}$ és $f_{2,AD}$ faktorai

What the above formulae express is, in essence, that the thickness of the dispersing agent is *directly* proportional to the *size of the particles* in the dispersed phase, and the proportionality ratio depends on the volumetric ratio of the dispersing agent and the dispersed phase. One of the tasks of a concrete engineer in connection with this topic is to determine – for concrete constituents – the volumetric ratio that achieves the optimum dispersing agent thickness in relation with the distribution of the dimensions of solid particles, in order to reach the targeted consistency.

3. Results and evaluation of plant observations

3.1. General data

Consistency was measured by the flow table test acc. to EN 12350-5 within 15±5 minutes of the start of mixing the concrete. The compositional properties of the mixes examined were hardly altered from those described in Table 5 of [6], although the database had been updated with the data from new mixes. The current data is summarised in Table 11. More detailed data on the concrete composition content indicators of the mixes prepared with admixtures are summarised in Table 12. It can be realised from the data in Table 12 that the mixing plant produced an overwhelming majority of concrete mixes of F2 and F3 consistency according to EN 206-1, according to its customer orders.

A general presentation of the data would be incomplete without showing the range limits of the variations in *particle*

distributions of the mixes of sand and gravel fractions. The distribution curves of all aggregate mixes have been condensed into the single diagram in Fig. 29, which shows the distribution according to the *surface area pass* calculated for the unit of volume rather than the volume or mass percentage pass. It can be seen that there are considerable differences in the volumetric specific surface areas over 0.5 mm particle size, changing between 4000-6000 m²/m³. The influence of the volumetric specific surface area is, therefore, expected to be a major factor when considering the consistency of the mixes.

Fig. 29. Surface area distribution of aggregate mixes used between 2008-2011 (the single curve that leaves the chart is for sand with a volumetric specific surface area of ~12 000 m²/m³)

29. ábra A 2008-2011 között felhasznált adalékanyag-keverékek felületeloszlásai (az ábrából kifelé egyenlő görbe egy ~12 000 m²/m³ térfogati fajlagos felületű homokhoz tartozik)

3.2. Relationship between consistency and concrete composition content indicators

In processing the results of the observations, correlations were initially sought in the data of *mixes made without admixtures*, and the basic equations derived from the analysis were later used for compositions containing admixtures to calculate *factors* that expressed the effects of the admixtures. The equation that was found to match most closely the observed measured results is shown in Eq. (39).

$$\text{Flow}[\text{mm}] = (1 + f_{1,AD} \cdot \lambda_{AD}) \cdot f_{2,AD} \cdot A \cdot \frac{\left(\frac{x}{f_z}\right)^{n_x}}{\left(1 + \frac{a \cdot f_a}{z \cdot f_z}\right)^{n_f} \cdot \left(1 + \frac{a}{z}\right)^{n_a}} \quad (39)$$

where:

Flow is the estimated flow value [mm] of the concrete mix by flow table,

λ_{AD} is the dose of admixture in the volumetric ratio of paste powder (concrete composition content indicator),

$f_{1,AD}$ is the *dose factor* of the admixture (for specific values of the observed admixtures, see Table 12),

$f_{2,AD}$ is the factor typical of the *material* of the admixture (for specific values of the observed admixtures, see Table 12),

A is the experimental constant, in this case $A=39386.8$,

n_x , n_f and n_a are exponents, with observed values as follows:

$$n_x=0.288, n_f=1.208 \text{ and } n_a=0.319,$$

f_z is the volumetric specific surface area of the paste powder [m^2/m^3],

f_a is the volumetric specific surface area of the aggregate [m^2/m^3], z is the volumetric ratio of paste powder in the concrete, a is the volumetric ratio of aggregate in the concrete, and the other notations are the same as for Eqs. (37) and (38).

The correlation is quite *weak* ($R^2 \approx 0.29$), which is not surprising in the case of consistency, but the significance of the equation's multiplication factor was proved with a probability of $p=0.06$. The confidence interval for the flow values obtained from estimates was ± 88 mm at a probability level of 95% and ± 36 mm at a probability level of 67%. An interesting feature of the relationship is that when $a=0$ (that is, for pure paste) it assumes the *maximum value*, which complies with the principles defined by *Alexanderson*. What is new is that it also takes into account the influence of the dose of admixture (λ_{AD}), as well as its *effectiveness* ($f_{1,AD}$) and the influence of its type ($f_{2,AD}$). For the latter, a value that very closely approaches unity was obtained during the plant observations (see Table 12). Where mixes without admixture are concerned, the equation gives the estimated flow values for mixes with only water added, since $f_{1,AD} = f_{2,AD} = 1$ if $\lambda_{AD}=0$.

The flow values estimated from Eq. (39) must be regarded as *expected* values, which can assume any value within the confidence interval given above, but the calculated values are the *most probable (expected)* values. A few illustrations from processing the results are shown in Figs. 30 to 33. It can be realised from Fig. 33 that for a given w/c range and paste

Fig. 30. Expected flow values for mixes made without admixture ($\lambda_{AD}=0$) in the observed p-x range

30. ábra Adalékszer nélküli ($\lambda_{AD}=0$) keverékek terüleaseinek várható értékei a megfigyelt p-x tartományban

Fig. 31. Expected flow values for medium ($\lambda_{AD}=0.016$) doses of MRWR admixture in the observed p-x range

31. ábra Erős hatású adalékszer (MRWR) közepes ($\lambda_{AD}=0.016$) adagolása mellett elérhető területek várható értékei a megfigyelt p-x tartományban

Fig. 32. Expected flow values for high ($\lambda_{AD}=0.030$) doses of HRWR admixture in the observed p-x range

32. ábra Nagyon erős hatású adalékszer (HRWR) magas ($\lambda_{AD}=0.030$) adagolása mellett elérhető területek várható értékei a megfigyelt p-x tartományban

Fig. 33. Consistencies obtained with different admixtures, and without admixtures, depending on dosage, in the case of concrete mixes with a paste content of 280 l/m^3 , air content of 20 l/m^3 , and no additions

33. ábra A különböző adalékszerekkel, és azok nélkül elérhető konzisztenciák az adagolás függvényében 280 liter/m^3 pértartalmú, 20 liter/m^3 levegőtartalmú, kiegészítőanyagot nem tartalmazó betonkeverékek esetén

content, a high dosage of the medium range admixture may perform almost identically to a medium dosage of high range admixture. Increasing the dosage of admixture within a certain limit is a more significant influence than increasing the w/c ratio.

4. Material balance equations of concrete mixes

According to the definition given in the EN 206-1 European Standard concrete is a “material formed by mixing cement, coarse and fine aggregate and water, with or without the incorporation of admixtures, additions or fibres, which develops its properties by hydration” [9]. In addition to this definition – taking account of recent developments in the field of concrete engineering – the simple basic model for concrete mixes also regards concrete in its fresh state as a *macroscopically heterogeneous composite system* consisting of *solid phase (aggregates)*, *liquid phase (paste)* and *gaseous phase (air)*, in which the *paste* is itself a heterogeneous system, likewise consisting of *three* separate phases, which are:

- solid phase *paste powder* (cement, as a hydraulic bonding agent, perhaps together with (a mixture of) fine-grain *additions*, which are inert or have pozzolanic reactivity, latent hydraulic reactivity, etc.),
- liquid phase *water* (which may also contain one or more dissolved *admixtures*) and
- gaseous phase *air* (which may be intentionally added air bubbles by air entraining admixture, or just randomly remaining voids due to incomplete compaction).

A V_{concrete} [m³] volume of (fresh) concrete mix generally consists of five *main* concrete constituent components, while certain concrete constituents may themselves be made up of mixtures of sub-constituents (in known proportions):

K_{virt} [kg]: total additions; $K_{\text{virt}} = \sum (\alpha_{M,K_{\text{virt},i}} K_{\text{virt},i})$, where $\alpha_{M,K_{\text{virt},i}}$ is the *mass ratio* of the i^{th} $K_{\text{virt},i}$ [kg] addition component, and where $0 \leq \alpha_{M,K_{\text{virt},i}} \leq 1$ and $\sum \alpha_{M,K_{\text{virt},i}} = 1$,

c [kg]: quantity of cement added,

AG_{virt} [kg]: total (wet) aggregates; $AG_{\text{virt}} = \sum (\alpha_{M,AG_{\text{virt},j}} AG_{\text{virt},j})$, where $\alpha_{M,AG_{\text{virt},j}}$ is the *mass ratio* of the j^{th} $AG_{\text{virt},j}$ [kg] aggregate component, and where $0 \leq \alpha_{M,AG_{\text{virt},j}} \leq 1$ and $\sum \alpha_{M,AG_{\text{virt},j}} = 1$,

W_{virt} [kg]: quantity of water *added when blending the concrete mix*,

AD [kg]: total admixtures; $AD = \sum (\alpha_{M,AD,k} AD_k)$, where $\alpha_{M,AD,k}$ is the *mass ratio* of the k^{th} AD_k [kg] admixture component, and where $0 \leq \alpha_{M,AD,k} \leq 1$ and $\sum \alpha_{M,AD,k} = 1$.

$$\begin{pmatrix} \sum_{i=1}^{n_K} \alpha_{M,K_{\text{virt},i}} \cdot \frac{\Phi_{K,i}}{\rho_{K,i}} & \frac{1}{\rho_c} & \sum_{j=1}^{n_{AG}} \alpha_{M,AG_{\text{virt},j}} \cdot \frac{\Phi_{AG,j}}{\rho_{AG,\text{fine},j}} & 0 & \sum_{k=1}^{n_{AD}} \alpha_{M,AD,k} \cdot \left(\frac{1}{\rho_{AD,k}} - \frac{1 - SZ_k}{\rho_w} \right) \\ - \sum_{i=1}^{n_K} \alpha_{M,K_{\text{virt},i}} \cdot SW_{K,i} & - \frac{SW_c}{\rho_w} & \sum_{j=1}^{n_{AG}} \alpha_{M,AG_{\text{virt},j}} \cdot \frac{W_{AG,j} - SW_{AG,j}}{\rho_w} & \frac{1}{\rho_w} & \sum_{k=1}^{n_{AD}} \alpha_{M,AD,k} \cdot \frac{1 - SZ_k}{\rho_w} \\ \sum_{i=1}^{n_K} \alpha_{M,K_{\text{virt},i}} \cdot \frac{1 - \Phi_{K,i}}{\rho_{K,i}} & 0 & \sum_{j=1}^{n_{AG}} \alpha_{M,AG_{\text{virt},j}} \cdot \frac{1 - \Phi_{AG,j}}{\rho_{AG,\text{coarse},j}} & 0 & 0 \\ 0 & \frac{1}{\rho_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sum_{k=1}^{n_{AD}} \frac{\alpha_{M,AD,k}}{\rho_{AD,k}} \end{pmatrix} \begin{pmatrix} K_{\text{virt}} \\ c \\ AG_{\text{virt}} \\ W_{\text{virt}} - \Delta W_{\text{ev}} \\ AD \end{pmatrix} = \begin{pmatrix} \frac{p}{1+x} \cdot V_{\text{concrete}} \\ \frac{p}{1+x} \cdot x \cdot V_{\text{concrete}} \\ (1-p-l) \cdot V_{\text{concrete}} \\ \chi_c \cdot \frac{p}{1+x} \cdot V_{\text{concrete}} \\ \sum_{k=1}^{n_{AD}} \lambda_{AD,k} \cdot \frac{p}{1+x} \cdot V_{\text{concrete}} \end{pmatrix} \quad (40)$$

“Note: the “virt” (virtual) symbol used above expresses that parts belonging to the *different phases* of the concrete are (or may be) present in the concrete constituent components. For example, the part of the addition material which is *larger than* 0.063 mm is included in the solid phase of the aggregate, while the part of the aggregate which is *smaller than* 0.063 mm is included in the fluid paste as paste powder. The water which adheres to the surface of the aggregate, and which in many cases is not negligible, is also included in the paste – as a liquid – so in addition to the W_{virt} added water, this must also be taken into consideration in the liquid phase of the concrete.

The *structural composition* of concrete mixes described by the *mass data* above may also be basically described using *five* dimensionless ratios:

p : the volumetric ratio of paste in the concrete ($0 < p \leq 1$),

x : the volumetric ratio of the (free) liquid and the paste powder in the paste ($x > 0$, but generally in practice: $\sim 0.6 \leq x \leq \sim 3.6$),

l : the volumetric ratio of air (void) in the concrete ($0 \leq l < 1$, generally in practice: $\sim 0.010 \leq l \leq \sim 0.060 \dots 0.120, \dots$),

χ_c : the volumetric ratio of cement in the paste powder ($0 < \chi_c \leq 1$, if the paste is pure cement $\chi_c = 1$),

λ_{AD} : the *combined* volumetric ratio of the admixture compared with the paste powder, (where the $\lambda_{AD,k}$ ratios of individual – different effect – admixture components are $\lambda_{AD,k} \geq 0$, where the concrete mix contains no admixture $\lambda_{AD,k} = 0$; in general, however, $\lambda_{AD,k} \sim 0.005 \dots 0.050$, and is therefore a small value).

The correlations between the concrete composition content indicators and the amounts of the given concrete constituents with known physical properties are defined by the system of linear equations in the matrix equation shown in Eq. (40), where:

$\Phi_{K,i}$: the part of the i^{th} addition component which is smaller than 0.063 mm, as mass ratio,

$\rho_{K,i}$ [kg/m³]: the dried particle density of the i^{th} addition component,

ρ_c [kg/m³]: the particle density of the cement (in dry state),

$\Phi_{AG,j}$: the part of the j^{th} aggregate component which is smaller than 0.063 mm, as mass ratio,

$w_{AG,j}$: the moisture content of the j^{th} aggregate component as mass ratio,

$\rho_{AG,j, \text{fine}}$ [kg/m³]: the dried particle density of the part of the j^{th} aggregate component which is smaller than 0.063 mm,
 $\rho_{AD,k}$ [kg/m³]: the density of the k^{th} admixture component,
 sz_k : the dry content of the k^{th} addition component, as mass ratio,

ρ_w [kg/m³]: water density,

$sw_{K,i}$: (short-term) water absorption of the i^{th} addition component, as mass ratio,

sw_c : (short-term) water absorption of cement, as mass ratio,

$sw_{AG,j}$: (short-term) water absorption of the j^{th} aggregate component, as mass ratio,

$\rho_{AG,j, \text{coarse}}$ [kg/m³]: the dried particle density of the part of the j^{th} aggregate component which is larger than 0.063 mm,

ΔW_{ev} [kg] the water that evaporates from the concrete mix with a volume V_{concrete} [m³] until it is worked in,

$\lambda_{AD,k}$: the ratio of the volume of the k^{th} admixture component compared with the volume of the paste powder,

the other notations are the same as previously explained.

The system of linear equations presented in the matrix equation of Eq. (40) is fundamental in the mix design, determining the composition of concrete mixes. The system of equations expresses the fact that (fresh) concrete mixes are made up of a linear combination of the constituent phases of components. The matrix factor that may be regarded as known in the product on the left hand side of the equation (materials property matrix) contains the physical properties and compositional proportions (e.g.: fraction ratios) of the concrete constituent materials, while the vector factor of the product (mix composition vector) expresses the masses of the concrete constituents which are to be added - and which may be regarded as unknown during mix design. The so-called structural vector on the right hand side of the equation contains the volumes of paste powder, paste fluid and aggregates in a designed volume of concrete, as well as the volume of cement and the volume of the admixtures, respectively. The structural vector directly depends on the targeted concrete composition content indicators, which are either already known during mix design, or are determined on the basis of prior knowledge of particular correlations.

The mix composition vector and the structural vector mutually define each other in a clear way, so the design of the composition of concrete mixes is possible by solving the matrix equation of Eq. (40). During concrete mix design for a volume V_{concrete} , the first step is to determine the concrete composition content indicators, from which the structural vector on the right hand side of the matrix equation of Eq. (40) can be obtained. The matrix equation of Eq. (40) can be set up by the materials property matrix that contains the material properties and particular component proportions. The solution of the system of linear equations provides the mix composition vector, which produces, as a direct result, the quantities of the concrete constituents that are to be added to the targeted concrete mix with a volume V_{concrete} .

It should be noted that Eq. (40) (and therefore the concrete mix) may only be clearly defined if all the concrete composition content indicators are known. It also follows that fully comprehensive consequences can in theory only be drawn from observations related to concrete mixes, if the influence of each

concrete composition content indicator has been taken into account and evaluated.

5. Using the simple basic model to design the composition of concrete mixes to meet given criteria

Several concrete mix design methods are available which meet pre-defined criteria. The common principle behind the different methods is to search for compositions which meet the criteria by counting back from the design criteria (e.g. compressive strength and consistency), which assumes that accepted correlations are available, as is the case with the Palotás-Bolomey [10,11] and Ujhelyi [2] methods used widespread in Hungary for concretes without admixtures.

New correlations are necessary for concrete mix design with admixtures. The simple basic model for concrete mixes provides this opportunity: the use of material balance equations is included, and greater flexibility in applying correlations with a restricted range of validity in connection with the influences of factors is offered; that are developed through experiments.

In the followings, a specific example illustrates the essence of the method.

6. Example for concrete mix design

The present example details the steps of concrete mix design by the simple basic model for a concrete mix with designation C30/37-XC3-16-F4-MSZ 4798-1:2004.

6.1 Identifying and determining requirements

Compressive strength: The concrete in the example needs to have a characteristic compressive strength of $f_{ck, \text{cube}}$ according to MSZ EN 206-1 standard that lies between the minimum values for compressive strength prescribed for compressive strength classes C30/37 and C35/45, i.e. $37 \text{ N/mm}^2 \leq f_{ck, \text{cube}} < 45 \text{ N/mm}^2$. It is possible to ensure the characteristic compressive strength in continuous production if the mean compressive strength of the concrete meets the condition of $f_{cm} \geq f_{ck, \text{cube}} + 1.48 \times \sigma$, where $\sigma \geq 3 \text{ N/mm}^2$ is acceptable in the example. The estimate for the standard deviation of a population is recorded at 10% of the expected mean compressive strength of the concrete in the example, and the range of values for characteristic compressive strength is narrowed by 10% at both the upper and lower limits for safety reasons (which results $37.8 \text{ N/mm}^2 \leq f_{ck, \text{cube}} < 44.2 \text{ N/mm}^2$). The achieved result safely fulfil the given conditions for compressive strength if the mean compressive strength lies in the range $44.4 \text{ N/mm}^2 \leq f_{cm} < 51.9 \text{ N/mm}^2$.

Consistency: The flow value [mm] prescribed for consistency class F4 according to MSZ EN 206-1 standard lies in the range $490 \text{ mm} \leq \text{Flow} \leq 550 \text{ mm}$. In view of the uncertainties in estimating consistency, the range midpoint of $\text{Flow} = 520 \text{ mm}$ has been taken as the criterion.

Composition criteria: The recommendations according to MSZ EN 206-1 standard for exposure class XC3 are $w/c \leq 0.55$ and $c \geq 280 \text{ kg/m}^3$. Further requirements in Hungary are the minimum body density of fresh concrete of 2380 kg/m^3 and the minimum body density of hardened concrete of 2310 kg/m^3 .

Components of concrete		Mass ratios in constituents		volumetric specific surface	fine-content (<0.063 mm)		Dry densities		Moisture content		Absorption of water	
marking	name	marking	value	[m ² /m ³]	marking	[m%]	marking	[kg/m ³]	marking	[m%]	marking	[m%]
W _{virt}	water							ρ _w = 999				
AD	MRWR admixture	a _{M,AD,1} =	1,000					ρ _{AD,1} = 1070	1-sz ₁ = 70,0%			
c	CEM II/A-M (V-LL) 42,5 N			f _c = 1208000				ρ _c = 3000			sw _c = 1,51%	
K _{virt}	inert basalt powder	a _{M,Kvirt,1} =	1,000	f _K = 1456000	Φ _{K,1} =	88,0%		ρ _{K,1} = 2763			sw _{K,1} = 0,50%	
	0/4 _{virt}	a _{M,AGvirt,1} =	0,451	9859	Φ _{AG,1} =	0,4%		ρ _{AG, fine,1} =		W _{AG,1} = 3,49%	sw _{AG,1} = 0,20%	
								ρ _{AG, coarse,1} =				
AG _{virt}	4/8 _{virt}	a _{M,AGvirt,2} =	0,280	1365	Φ _{AG,2} =	0,3%		ρ _{AG, fine,2} =		W _{AG,2} = 1,71%	sw _{AG,2} = 0,95%	
				fa = 5034				ρ _{AG, coarse,2} =				
	8/16 _{virt}	a _{M,AGvirt,3} =	0,269	926	Φ _{AG,3} =	0,2%		ρ _{AG, fine,3} =		W _{AG,3} = 1,21%	sw _{AG,3} = 0,95%	
								ρ _{AG, coarse,3} =				

Table 13. Data of the concrete constituents that are available for concrete with designation C30/37-XC3-16-F4-MSZ 4798-1:2004, which is to be designed in the example (note: sz₁ refers to dry content of the MRWR admixture)

13. táblázat A példa szerint tervezendő C30/37-XC3-16-F4-MSZ 4798-1:2004 jelű betonhoz rendelkezésre álló betonalkotók adatai

Type of cement taken into account	Content (stuctural) indicators						Other technical data		
CEM II A-M (V-LL) 42,5 N	p	x	χ_c	λ_{AD}	I	traditional w/c	a*	D _{max} mm	
Augusztin Betongyártó Ltd. 2008-2010. 46 observations	min.	0.204	1.294	0.750	0.010	0,000	0.484	0.686	8
	max.	0.302	2.327	0.974	0.026	0.041	1.048	0.756	32
	AVG.	0.261	1.753	0.822	0.019	0.012	0.729	0.727	24,5
	STD.	0.016	0.243	0.055	0.006	0.007	0.138	0.014	8

Augusztin Betongyártó Ltd.
2008-2010.
46 observations

Table 14. Concrete composition content indicators and other data of CEM II/A-M (V-LL) 42.5 N mixes evaluated during industrial observations (a*: volumetric ratio of the aggregate in the concrete mix)

14. táblázat Az üzemi megfigyelések során értékelésbe vont CEM II/A-M (V-LL) 42,5 N keverékek betonösszetételi állapotjelzői és néhány más adata (a*: a betonkeverékben lévő adalékanyag térfogataránya)

Admixture code	Observations (no.)	p – paste volumetric ratio		x – liquid-powder volumetric ratio factor		λ – dose of admixture in the paste powder volumetric ratio			Measured Flow [mm]		Factors in the estimation formula	
		ρ _{min}	ρ _{max}	χ _{min}	χ _{max}	λ _{min}	λ _{AVG}	λ _{max}	Flow _{min}	Flow _{max}	f _{1,AD}	f _{2,AD}
MRWR	10	0.212	0.314	0.924	1.872	0.008	0.016	0.030	340	590	8.868	1.012

Table 15. Data on the concrete composition content indicators and consistency measurements of mixes made by mid-range water-reducing MRWR admixture, and the f_{1,AD} and f_{2,AD} factors of the consistency estimation formula of Eq. (42)

15. táblázat Az erős hatású adalékszerrel (MRWR) készített keverékek betonösszetételi állapotjelzőinek és konzisztencia mértékszámainak adatai, valamint a konzisztenciabecslő (42) képlet f_{1,AD} és f_{2,AD} faktorai

No	Target parameters and content indicators							Composition (for dry aggregates) kg/m³					Design composition (for wet aggregates) kg/m³							Checking		
	f _{cm28,exp} [N/mm²]	Flow _{exp} [mm]	p	χ _c	I	x	λ _{AD} (MRWR)	CEM II/ A-M 42.5	AG	W	AD ₁ (MRWR)	stone pow- der	CEM II/ A-M 42.5	0/4 sand	4/8 gravel	8/16 gravel	W _{virt}	AD ₁ (MRWR)	w/c	ρ _{fresh} kg/m³	expo- sure class	
1	44,4	520	0,280	0,850	0,020	1,333	0,034	46	306	1849	173	4,32	46	306	853	530	509	129	4,32	0,54	2379	XC3
2	44,4	520	0,280	0,972	0,020	1,560	0,030	-0	319	1854	184	3,54	-0	319	856	532	510	140	3,54	0,55	2361	XC2
3	44,4	520	0,300	0,850	0,020	1,317	0,030	51	330	1795	184	4,11	51	330	829	515	494	141	4,11	0,53	2365	XC2
4	44,4	520	0,300	0,975	0,020	1,559	0,026	-0	343	1801	197	3,27	-0	343	831	517	496	154	3,27	0,55	2344	X0
5	51,9	520	0,280	0,850	0,020	1,183	0,036	50	327	1848	165	4,91	50	327	853	530	509	121	4,91	0,48	2395	XC4
6	51,9	520	0,280	0,973	0,020	1,408	0,032	-0	339	1854	177	3,96	-0	339	856	532	510	133	3,96	0,50	2375	XC3
7	51,9	520	0,300	0,850	0,020	1,168	0,032	55	353	1795	175	4,72	55	353	828	515	494	133	4,72	0,47	2382	XC3
8	51,9	520	0,300	0,976	0,020	1,396	0,028	-0	366	1801	189	3,72	-0	366	831	517	496	146	3,72	0,49	2360	XC2

Table 16. The composition calculations performed on the basis of the example criteria, where f_{cm28,exp} and Flow_{exp} are the assumed design criteria (target parameters), p, χ_c and I are freely selected, and x, λ_{AD} are calculated content indicators dependent on the preceding. The Table contains the recipes derived from solving the matrix equation of Eq. (40), mixing instructions (for wet aggregate components) and a control column for the exposure requirements

16. táblázat A példa szerinti kritériumok alapján végzett összetétel-számítások, ahol az f_{cm28,exp} és Flow_{exp} felvett tervezési kritériumok (célparaméterek), p, χ_c és I szabadon választott, az x, λ_{AD} pedig ezekről függő számított állapotjelzők. A táblázat tartalmazza a (40) egyenletrendszer megoldásából kapott receptúrákat, keverési utasításokat (nedves adalékanyag-komponensekre) és egy ellenőrző blokkot a kitéti követelményekre

6.2 Identifying the concrete constituent materials and determining their properties

The example does not take the quantity of evaporating water into consideration, so $\Delta W_{ev}=0$, and the other available materials and their properties are listed and presented in Table 13 and in Fig. 34.

Fig. 34. Data on the particle distribution of aggregates that are available for concrete with designation C30/37-XC3-16-F4-MSZ 4798-1:2004, which is to be designed in our example.

34. ábra A példa szerint tervezendő C30/37-XC3-16-F4-MSZ 4798-1:2004 jelű betonhoz rendelkezésre álló adalegényanyagok szemeloszlási adatai

6.3 Identifying the correlations related to the design criteria as target parameters

Instead of searching for new, universally valid correlations, the simple basic model for concrete mixes preferably relies on local correlations, obtained through *experience* from *controlled experimental data*, whose validity is restricted to the materials used in the given experiment and their range of interpretation. Such experimental correlations may be obtained at any concrete mixing plant where industrial production is controlled under supervision by trained professional concrete technicians.

The correlations obtained through experience are used here that relate to compressive strength and to consistency. Validity extends to the concrete constituents identified in paragraph 6.2. 46 observations are available for the compressive strength of mixes made from CEM II/A-M (V-LL) 42.5 N cement, and 10 observations are available for the consistence of mixes with MRWR admixture (see Tables 14 and 15).

For the experiential correlations used for compressive strength Eq. (33) applies, but replacing $f_{c,28}$ with $f_{c,28,exp}$ which is the expected mean compressive strength of concrete at the age of 28 days, see Eq. (41).

$$f_{c,28,exp} = A \cdot \frac{\chi_c^{n_x} \cdot p^{n_p}}{(1+x)^{n_x}} \cdot (1-l)^{n_l} \quad (41)$$

where:

$f_{c,28,exp}$ [N/mm²] is the target mean compressive strength measured on cube specimens after 28 days standard curing, A is the experiment constant, for CEM II/A-M (V-LL) A=342.302, χ_c is the cement volumetric ratio in the paste powder, n_x is the exponent of χ_c , for CEM II/A-M (V-LL) $n_x=1.711$, p is the paste volumetric ratio in the concrete, n_p is the exponent of p, for CEM II/A-M (V-LL) $n_p=-0.240$, x is the liquid-paste volume factor in the paste, n_x is the exponent of (1+x), for CEM II/A-M (V-LL) $n_x=2.355$, l is the air volumetric ratio in the concrete, n_l is the exponent of l, for CEM II/A-M (V-LL) $n_l=3.75$.

For the experiential correlations used for consistence Eq. (39) applies, but replacing Flow with $Flow_{exp}$ which is the *expected* mean flow value of the fresh concrete mix, see Eq. (42).

$$Flow_{exp} [mm] = (1 + f_{1,AD} \cdot \lambda_{AD}) \cdot f_{2,AD} \cdot A \cdot \frac{\left(\frac{x}{f_z}\right)^{n_x}}{\left(1 + \frac{a \cdot f_a}{z \cdot f_z}\right)^{n_f} \cdot \left(1 + \frac{a}{z}\right)^{n_a}} \quad (42)$$

where:

$Flow_{exp}$ is the expected mean flow value [mm] of the concrete mix by flow table,

λ_{AD} is the dose of admixture in the volumetric ratio of paste powder (concrete composition content indicator),

$f_{1,AD}$ is the *dose factor* of the admixture (for specific values of MRWR see Table 15),

$f_{2,AD}$ is the factor typical of the *material* of the admixture (for specific values of MRWR see Table 15),

A is the experimental constant, in this case A=39386.8,

n_x , n_f and n_a are exponents, with observed values as follows: $n_x=0.288$, $n_f=1.208$ and $n_a=0.319$,

f_z is the volumetric specific surface area of the paste powder [m²/m³], in this case $f_z \approx \chi_c f_c + (1-\chi_c) f_k$, (f_c and f_k according to Table 13),

f_a is the volumetric specific surface area of the aggregate [m²/m³], in this case f_a according to Table 13,

z is the volumetric ratio of paste powder in the concrete ($z=p/(1+x)$),

a is the volumetric ratio of aggregate in the concrete ($a=1-l-p$).

Finally, the correlations to be considered due to the restriction $w/c \leq 0.55$ can be given by Eq. (43).

$$x \approx \chi_c \cdot \left(\frac{w}{c} - sw_c \right) \frac{\rho_c}{\rho_f} \quad (43)$$

where ρ_f is the mean density of the liquid constituents in the concrete (mostly water).

Substituting the data in Eq. (43) ρ_c and sw_c from Table 13 and $\rho_f=1000$ kg/m³ gives Eq. (44).

$$x \leq \chi_c \cdot (0.55 - sw_c) \frac{\rho_c}{\rho_f} = \chi_c \cdot (0.55 - 0.0151) \frac{3000}{1000} = 1.6047 \cdot \chi_c \quad (44)$$

6.4 Determining the concrete composition content indicators required to fulfil the criteria, and determining the possible mix compositions by solving the system of material balance equations

Concrete mixes are determined by *five* linearly independent content indicators, but there are *two* estimate formulae, Eqs. (41) and (42), and furthermore, one of the content indicators is assumed to have a value of $l=0.020$ (therefore with an air content of 20 litres/m³), so the number of concrete composition content indicators that may be freely selected is reduced to two, and even between x and χ_c there is the restriction given by Eq. (44). It is practical to freely select the values of p and χ_c , and to calculate – from the interactions of Eqs. (41), (42) and (44) – the possible content indicators x and λ_{AD} . After the five content indicators have been determined in this way, they also provide the *structural* vector

on the right hand side of Eq. (40), from which the matrix equation can be solved to find the mix composition vector. The calculations in the example have been performed for *paste contents* of 280 and 300 l/m³ ($p=0.280$ and $p=0.300$) and for addition *contents* of almost zero and 15 V% ($\chi_c=0.850$ and $\chi_c=0.972...0.976$) and the results of the calculations are presented in Table 16.

6.5 Discussion

Of the mix compositions presented in Table 16, mixes no. 1, 6 and 7 fulfil all the requirements, including those for body density – which are too strict in the opinion of the author of the present paper. The data in Table 16 show that there is not much to be gained by increasing the paste content in a given concrete and by targeting the *upper* limit within the strength class, as this involves an increase in the dose of cement, and furthermore the dose of water reducing admixture also needs to be increased. The mix that best meets the requirements is no. 1, in the opinion of the author of the present paper, even though mix no. 1 also has the blemish in that according to Table 15, the industrial observations were in the range $\lambda_{AD} < 0.030$, while here one can see $\lambda_{AD} = 0.034$, which is an *extrapolated* value. It would be possible to make adjustments by amending the flow value criterion, but it is not worthwhile, as even if $\lambda_{AD} = 0.030$, the estimated flow value is ~508 mm, which is a negligible difference to the designed 520 mm.

7. Present and future tasks in concrete engineering

Concrete engineering in the last few decades has witnessed the appearance of newer and newer types of cements and admixtures, and it is impossible for standard methods to keep up with technical developments when it comes to describing the effects of the new materials. This necessitated a new systematic and harmonised examination of the effects of concrete constituents, in order to gain a deeper insight into their effects. This is not just in the interest of the cement producers or the companies that distribute the admixtures, but also in the interest of concrete mixing plants. Research is already underway in many institutes separately. Author of the present paper has no doubt about the commitment of ÉMI Nonprofit Ltd in this sense: the research is ongoing in cooperation with scientific institutions and with smaller and larger concrete mixing plants, which have the objective of optimising concrete compositions and of improving the advancement of the technical culture in concrete mixing plants.

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Betonkeverékek egyszerűsített alapmodellje és alkalmazása

3. rész: Konzisztenciát befolyásoló tényezők, anyagmérleg egyenletek, összetételek tervezése

A gyártóüzemi megfigyelések során a konzisztenciára vonatkozóan is számos érdekes kérdés merült fel. A szerző véleménye szerint igazán értékelhető adathalmazt éppen a gyártóüzemekben (illetve a transzportbeton kiszállítási helyszínein) végzett vizsgálatokkal nyerhetünk. Mindazonáltal a statisztikai jellemzők a konzisztencia tekintetében korántsem igazolnak olyan szoros kapcsolatot, mint a szilárdság vagy az alakváltozás esetén, ezért a kellő óvatosság indokolt, bár az óvatosság sosem jelentheti azt, hogy legyintve mondjunk le bizonyos következtetések levonásáról. A betonösszetéti (strukturális) állapotjelzők bevezetése hasznos lehet a friss (és megszilárdult) betonkeverékek összetételének tervezése során is, amennyiben ismerjük, vagy kísérleti úton meghatározzuk a betonösszetéti állapotjelzők és a friss és megszilárdult beton tulajdonságai közötti összefüggéseket, és alkalmazzuk a betonkeverékek anyagmérleg egyenleteit. A cikksorozat befejező része ezeket a kérdéseket mutatja be.