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WATER DEMAND OF CONCRETE MIXTURES

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Abstract

After summarizing the former methods for evaluating water demand of concrete mixtures [1-17], the author gives some information about his investigations of the last twenty years carried out in Hungarian Institute for Building Sciences, sponsored partly by Ministry for Building (1975-1985), partly by National Organization of Technical Development in Hungary, OMFB, (1989-1992), partly by National Foundation for Scientific Research in Hungary, OTKA (1992-1994).

The detailed results came – as by-products – from these investigations, which had the aim to determine possibilities and criteria of making durable concretes. According to the results, the water demand of concretes may be separated into three stages:

(a) mixture of water and aggregate with cement content from zero to a relatively small quantity (depending on the aggregate grading up to 150-250 kg/m^3), where the necessary water quantity (in kg/m^3) for a given workability is constant and depends only on the aggregate grading (from aggregate+water up to lean concrete mixtures),

(b) mixture of cement, water and aggregate with cement content from 150-250 kg/m^3 up to 600-700 kg/m^3, where the necessary water quantity depends on the aggregate grading but increases slowly with increasing cement content (ordinary concrete mixtures),

(c) mixtures from very rich concretes (cement content of about 600-700 kg/m^3) up to cement pastes, where the necessary water content for a given workability depends mainly on cement content (pastes or paste-like mixtures).

The paper deals with the calculation method of necessary water quantity depending on cement content and fineness (specific surface), on aggregate grading (type and fineness) and on necessary workability.

Keywords: fresh concrete, workability, mix design.

1. Introduction

Every important characteristic of fresh concrete, as consistency, workability, cohesiveness, etc. depends on the mixing water quantity. The correct determination of water demand in concrete mixture, i.e. of water content required to the suitable workability, has engrossed the attention of concrete technologists long before. It has been particularly important, since the requirements concerning concrete properties are nowadays more severe than earlier.

Knowing water demand is also needed for pre-estimation of mechanical and physical properties of hardened concrete and for concrete mix design. The water content influences not only the compressing and tensile strength of concrete but its setting and hardening processes, freezing-thawing resistance, abrasiveness, permeability, shrinkage, creep, durability, etc. Therefore the expected values of these properties can be calculated in a reliable manner only if the water demand can be correctly determined.

The internal friction of a granular heap can be diminished by wetting grain's surface, so several properties of fresh mixture may improve at higher water contents. On the other hand, properties of hardened concrete may be improved by decreasing pore content, which requires a reduction in mixing water. This conflict can be eliminated by optimization.

This paper deals briefly with some former methods of water demand estimation and gives results of investigation carried out on this problem by author.

2. Key of Symbols

m_c, m_w and m_a = weight of cement, water and aggregate in fresh, compacted concrete in kg/m^3

m_{ai} = weight of the i^{th} separated fraction of the aggregate in fresh, compacted concrete in kg/m^3

m_{ao} = weight of aggregate in fresh, fully compacted aggregate+water mixture in kg/m^3

m_s, m_{sf}, m_{sm} and m_{sc} = weight of sand (0–4 mm), fine sand (0–0.5 mm), medium sand (0.5-2 mm) and coarse sand (2–4 mm) respectively in fresh, compacted concrete in kg/m^3

m_g = weight of gravel (4–D mm) in fresh, compacted concrete in kg/m^3

m_{cp} and m_{wp} = weight of cement and water in fresh, compacted cement paste in kg/m^3

D = maximum grain size in mm

d_1 and d_2 = minimum and maximum grain size in a given size fraction of aggregate in mm

d_i = separate grain size in mm

ρ_c and ρ_a = specific gravity of cement and aggregate in g/cm^3

S = specific surface area of cement in m^2/kg (by Blaine)

V_c, V_w, V_a and V_1 = volume of cement, water, aggregate and air respectively in fresh, compacted concrete in $\mathrm{dm}^3/\mathrm{m}^3$

V_{ao} = volume of aggregate in fresh, fully compacted aggregate+water mixture in $\mathrm{dm}^3/\mathrm{m}^3$

w_c and w_a = water demand of cement and aggregate respectively in weight ratio

m_I =fineness modulus determined on ISO-A sieve series (from 0.063 mm)

m_A = fineness modulus of ABRAMS (investigated on Tyler sieve series)

x water–cement ratio by weight

3. Former Methods of Water Demand Estimation

In principle, three method groups have been developed for water demand estimation.

The first group considers the concrete mixture as a blend of grains of different sizes and calculates the total water content as a sum of partial water demands. Some of these methods are described below.

According to FERET [1], the water content of the plastic concrete mixtures:

$$m_w = 0.235 \cdot m_c + 0.23 \cdot m_{sf} + 0.09 \cdot m_{sc} \ \mathrm{kg/m}^3 \tag{1}$$

since water demand of gravel is negligible.

BOLOMEY [2]suggested the following function for plastic concrete:

$$m_w = 0.27 \cdot m_c + \sum_{i=1}^{n} \frac{N \cdot m_{ai}}{\sqrt[3]{d_1 \cdot d_2}} \ \mathrm{kg/m}^3 \ , \tag{2}$$

where N = experimental constant, for crushed grains $N = 0.095 - 0.13$ and for rounded grains $N = 0.08 - 0.11$ (the finest fraction is 0.2–1 mm).

LEVIANT [3] proposed to determine the water content depending on average grain sizes:

$$m_w = 0.255 \cdot m_c + \sum_{i=1}^{n} m_{ai} \cdot \frac{0.072}{\sqrt{d_i}} \ \mathrm{kg/m}^3 \ . \tag{3}$$

It has to be noted that the finest sand has $d_i = 0.1$ mm and the cement $d_i = 0.08$ mm (since $0.072 : \sqrt{0.08} = 0.255$)

In the ÉTI the water demand of different fractions was investigated by HORVÁTH [4] with method of JOISEL [5]. The relationship is as follows:

$$m_w = 0.24 \cdot m_c + \sum_{i=1}^{n} m_{ai} \cdot 4.65 \cdot e^{-3.9 \cdot d_i^{0.1}} \ \mathrm{kg/m}^3 \ , \tag{4}$$

where for the finest sand: $d_i = 0.063$ mm.

The second group of methods considers the concrete as a mixture of cement and aggregate and attributes great value to water demand of cement. Some examples of these methods are as follows.

ABRAMS [6] suggested the following equation:

$$m_w = 0.23 \cdot m_c + k \cdot m_a \cdot \left(0.16 - \frac{m_A}{50}\right) \text{ kg/m}^3 , \qquad (5)$$

where k = constant depending on aggregate shape, e.g. for round grains $k = 1,2$.

The French Association of Bridge and Road [7] calculates the water quantity from the following function (for stiff concrete)

$$m_w = 0.23 \cdot m_c + 45 \text{ kg/m}^3 , \qquad (6)$$

i.e. the water demand of aggregate is considered constant: 45 kg/m^3.

Equation of SUENSON [8] is as follows:

$$m_w = 0.26 \cdot m_c + 0.02 \cdot m_g + \left[0.017 \cdot \left(\frac{m_g}{m_c + m_s}\right)^2 + 0.027\right) \cdot m_s \text{ .kg/m}^3 . \qquad (7)$$

According to ALEXANDERSON [9] the water demand of concrete to a given workability may be expressed by water–cement ratio (x). If pure cement paste is used, $V_a = 0$, $V_a : V_c = 0$ and water–cement ratio is x_0. If pure aggregate+water is used, $V_c = 0$, $V_a : V_c \rightarrow \infty$ and water–cement ratio $x \rightarrow \infty$, as it can be seen in *Fig. 1.*

POPOVICS [10] calculates the water content of concrete in lb/cu.yd. His equation for plastic consistency:

$$m_w = m_c \cdot \left\{0.1 + \frac{0.032[(2^{m_A} - 60)^2 + 6570]}{m_c - 100}\right\} \text{ lb/cu.yd} , \qquad (8)$$

(1 lb/cu.yd = 0.5932 kg/m^3).

The third group of methods starting from the water demand of aggregate and that of cement is taken in account only over a range of cement content, or with a small value. Some examples are as follows.

SCHOLZ [11] calculates the water demand of aggregate depending on 'grain factor' (Körnungsziffer) 'k'. The relationship between k and m_I is as follows:

$$k = (m_I - 1.4) : 1.58 , \qquad (9)$$

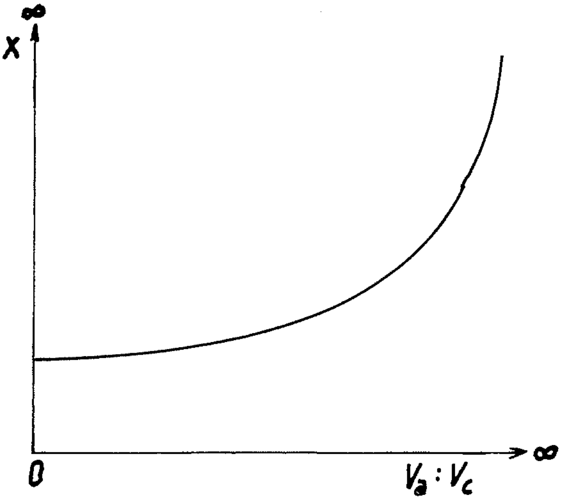

Fig. 1. Change of water–cement ratio according to [9]

therefore on the basis of figures given by SCHOLZ – according to my calculation – the water content of stiff concrete is

$$m_w = (m_c - 300) \cdot 0.1 + 726 \cdot e^{-\left(\frac{m_I - 1.4}{1.58}\right)^{0.38}} \ \mathrm{kg/m^3}\ , \qquad (10)$$

where the first member of equation has to be taken in account only for $m_c > 300 \mathrm{kg/m^3}$. For medium plastic, plastic and wet concretes the excess water quantity is +10, +20 and +30 kg/m^3, respectively [11].

ROTHFUCHS [12] determined the relationship between water content and 'size sum' (D-Summe: DS) which is sum of passing percentage on circular sieves of 0.2 , 1, 3, 7, 15, 30 and 70 mm. According to his figures:

$$m_w = (m_c - 300) \cdot 0.1 + \left(A + \frac{DS - 250}{350} \cdot B\right) \ \mathrm{kg/m^3}\ , \qquad (11)$$

where A and B for different consistencies are:

	stiff	medium plastic	plastic	wet
A	123	136	149	162
B	102	100	97	94

PALOTÁS [13] calculates the water content of stiff concrete from the following equation:

$$m_w = 0.1 \cdot m_c + 23 \cdot (10 - m_A) \text{ kg/m}^3 . \tag{12}$$

For other consistencies the thinning factors are: medium-plastic $\approx$ 1.15; plastic $\approx$ 1.25 and wet $\approx$ 1.35.

The nomogram for determination of mixing water made by KAUSAY [14] can be seen in *Fig. 2*, where the consistency is given by the compacting factor (k_{CF}). ARMUTH [15] found that water content in concretes of $m_c \leq$ 300 kg/m^3 is independent of cement content and for stiff consistency can be calculated from the following equation:

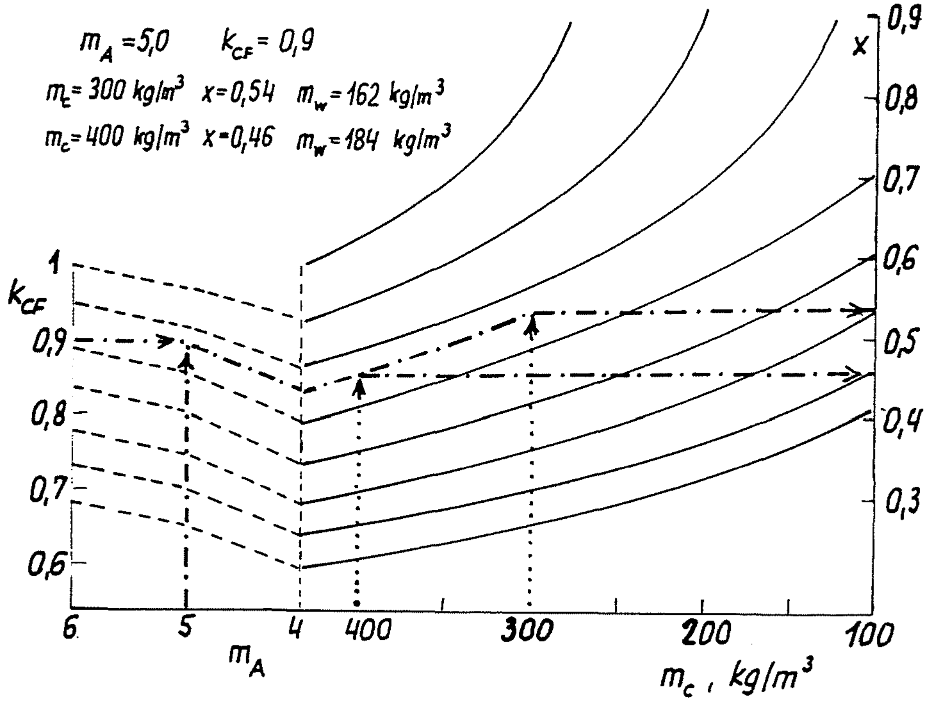

Fig. 2. Nomogram of KAUSAY to determine the mixing water [14]

$$m_w = 275 - 22.7 \cdot m_A \text{ kg/m}^3 . \tag{13}$$

For other consistencies thinning factors are the same as in *Eq.* (12).

According to SIZOV [16] the necessary water content is constant up to m_c = 300 kg/m^3. For higher cement content: $m_w = m_{wo} + \Delta m_w$, where

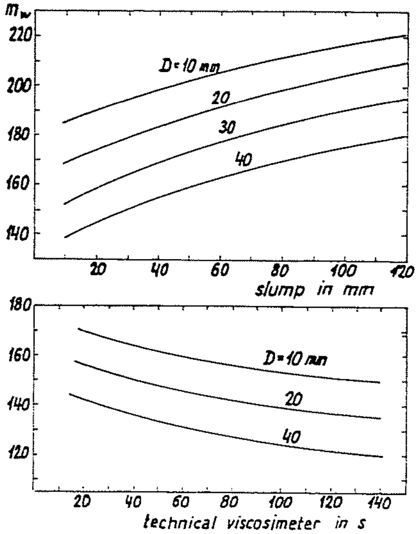

Fig. 3. Mixing water quantity according to BASHENOV [17]

Δm_w depends on the excess cement quantity. Values of m_{wo} according to BASHENOV [11] can be seen in *Fig. 3.*

4. Comparison of Results of Different Methods

Water contents calculated by different methods are summarized in *Fig. 4* for $m_c = 300$ kg/m^3 and plastic consistency. It is to be noted that in the calculation the specific gravity of cement was $\rho_c = 3.1$ g/cm^3 and that of aggregate $\rho_a = 2.64$ g/cm^3. Therefore volume of cement is: $V_c = m_c : 3.1$ dm^3/m^3 and that of aggregate is: $V_a = m_a : 2.64$ dm^3/m^3. For 1 m^3 (1000 dm^3) well compacted concrete exists the following relationship :

$$V_c + V_w + V_a + V_1 = 1000 \text{ dm}^3/\text{m}^3 \tag{14}$$

For instance $m_c = 300$ kg/m^3; $D = 16$ mm; $m_I = 5.56$ (0 − 0.5 mm=20%; 0.5 − 2 mm = 24%; 2 − 4 mm = 15% and 4 − 16 mm = 49%); $V_1 = 0$ dm^3/m^3; from (1) $m_w - 300 \cdot 0.235 + 0.23 \cdot 0.2 \cdot m_a + 0.09 \cdot 0.24 \cdot m_a + 0.03 \cdot 0.15 \cdot m_a = 70.5 + 0.0721 \cdot m_a$ kg/m^3 and from (14) if $V_0 = 0 : 1000 = (300 : 3.1) + (m_a : 2.64) + (70.5 + 0.721 \cdot m_a)$, therefore $m_a = (1000 - 167.3) : [(1 : 2.64) + 0.0721] = 1847$ kg/m^3, hence the water content according to FERET : $m_w = 70.5 + 0.0721 \cdot 1847 = 204$ dm^3/m^3 or kg/m^3.

It can be seen from *Fig. 4* that differences of calculated water content at medium fineness modulus ($m_I \sim 6.0$) are less than that at extreme

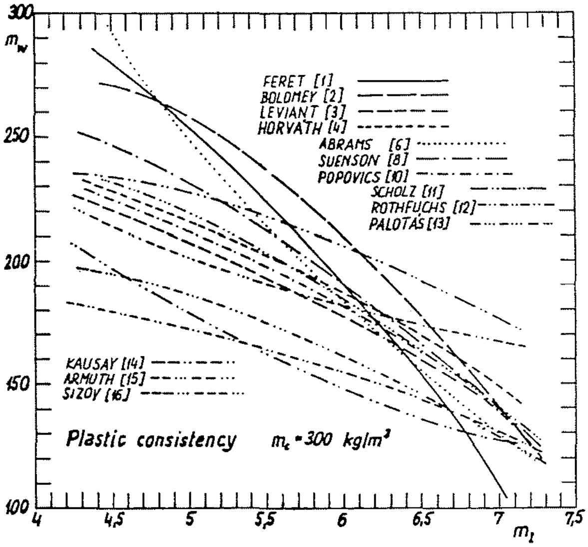

Fig. 4. Water content of concretes made with 300 kg/m^3 cement, calculated by different methods

moduli ($m_I = 4.5$ or 7.5). It may be supposed that aggregates of extreme gradings were investigated occasionally, the equations were fitted mainly for medium ones. Moreover, it can be stated that the results of calculation are not reliable enough for exact mix design, thus more precise estimation method is necessary.

5. Hypotheses for Water Demand Calculation

It is known that the water demand of aggregate depends on the grain surfaces to be wetted. Nevertheless, the mixing water cannot be calculated by summing-up water demand of every single grain, because

- the thickness of adhesive water layer on grain surface depends on the grain size ; the less the diameter the thicker the water layer is because of the higher surface tension of water,
- the water layer thickness on contact point of two grains is not accumulated,
- on contact points menisci are created causing water-surplus depending on number of grains,

as it can be seen in *Fig. 5.* Therefore water demand of an aggregate depends on more factors, such as surface of grains and numbers of contact points in

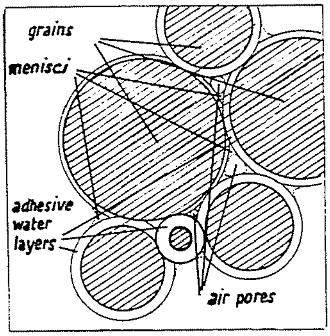

Fig. 5. Sketch of water in granular heap

the heap, as well as effects influencing water layer thickness (compaction, temperature).

In the concrete mixture the sizes of cement grains (μm) and that of aggregate grains (mm) are well separated, consequently their water demands have to be different. The granular material to be wetted can be pure cement and pure aggregate in extreme cases. If it is possible to determine the water demand of mixtures with different sizes (cement and aggregate) at the same consistency (workability), exact results can be obtained for extreme values too. Starting from these, the water demand of different cement: aggregate mixtures with the same consistency can be investigated and the type of function determined with good accuracy. This logical process can be seen in *Fig. 6*.

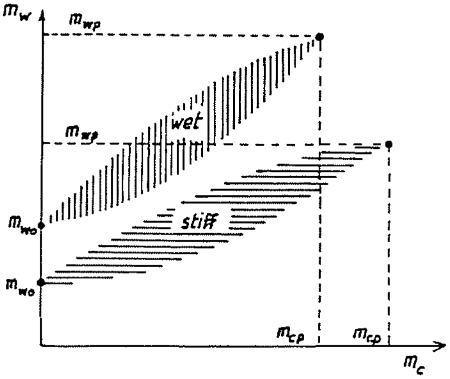

Fig. 6. Sketch of change in mixing water quantity

If cement paste is investigated and its water demand w_c (by weight ratio) is fitted for a given consistency, the following equality exists:

$$1000 = V_c + V_m = (m_{cp} : \rho_c) + w_c \cdot m_{cp} = m_{cp}[(1 : \rho_c) + w_c] \text{ dm}^3/\text{m}^3 \ , \quad (15)$$

therefore the paste composition:

$$m_{cp} = 1000 : [(1 : \rho_c) + w_c] \text{ kg/m}^3 \quad (16)$$

and

$$m_{wp} = w_c \cdot m_{cp} \text{ kg/m}^3 \ . \quad (17)$$

Example: there is a paste of plastic consistency, where $\rho_c = 3.1$ g/m^3 and $w_c = 0.28$. The paste composition is: $m_{cp} = 1000 : (1 : 3.1) + 0.28 = 1660$ kg/m^3 and $m_{wp} = 0.28 \cdot 1660 = 465$ kg/m^3.

If aggregate+water mixture is investigated and its water demand w_a (by weight ratio) is fitted for a given consistency, the following equality exists:

$$1000 = V_{ao} + V_w + V_1 = (m_{ao} : \rho_a) + w_a \cdot m_a + V_1 \text{ dm}^3/\text{m}^3 \quad (18)$$

therefore the composition of aggregate+water mixture is as follows:

$$m_{ao} = (1000 - V_1) : [(1 + \rho_a) + w_a] \text{ kg/m}^3 \quad (19)$$

and

$$m_{wo} = w_a \cdot m_{ao} \text{ kg/m}^3 \ . \quad (20)$$

Example: there is an aggregate+water mixture of plastic consistency, where $V_1 = 100$ dm/m^3, $\rho_a = 2.64$ g/cm^3 and $w_a = 0.1$. Its composition is: $m_{ao} = (1000 - 100) : (1 : 2.64) + 0.1 = 1880$ kg/m^3 and $m_{wo} = 1880 \cdot 0.1 = 188$ kg/m^3.

In these examples the ordinates of *Fig. 6* are as follows: $m_{wo} = 188$ kg/m^3 at $m_c = 0$ and $m_{wp} = 465$ kg/m^3 at $m_{cp} = 1660$ kg/m^3.

It is to be noted that the fully compacted fresh cement paste is always free from pores ($V_1 = 0$), but the aggregate+water mixtures have always some pore content ($V_1 > 0$) even if they had been perfectly compacted. Furthermore, surface tension of water varies depending on temperature: the higher the temperature the less the tension is. Therefore water demand has to be tested at constant temperature.

It is known that aggregates of high sand content (low fineness modulus) demand more water to a given consistency than the coarse ones. Therefore value m_{wo} increases with decreasing fineness modulus. From *Fig. 6* the conclusion can be drawn without investigation that making concretes of given consistency with the same cement but with different aggregate gradings, the rise of the temporarily unknown curve connecting the points of water content at m_{co} and m_{cp} is steeper at high fineness modulus than that at low one. Therefore it can be assumed that water demand of concrete made with coarse aggregate is influenced more by the cement content than that of concrete made with fine aggregate.

Investigation can be carried out for confirming this hypothesis if an apparatus suitable for determining consistency both of cement paste and aggregate+water mixture exists. In other words: a characteristic of mixtures has to be investigated which is in connection with the consistency and this characteristic should be kept on the same level.

Every known apparatus for determining consistency measures different characteristics of fresh concrete (slump test: cohesiveness, flow test: mobility, compacting factor: compactibility, Humm apparatus: internal friction, VEBE apparatus: paste retention capacity, remolding test: mouldableness, etc). It is obvious that these above mentioned apparatus can be used only if the mixture has some cohesiveness, but water+aggregate mixture segregates; therefore its 'consistency' cannot be investigated with the known instruments.

It is known from the literature [18] that the index number of consistency for concrete mixtures having the same workability may vary even within the usual concrete compositions, so the same consistency can hardly be set at cement contents between 125 and 500 kg/m^3. Therefore new equipment for measuring consistency had to be found for controlling mixtures of extreme composition (e.g. aggregate+water mixture).

One of the concrete workability characteristics is the water retention capacity. Simple instrument can be created for measuring this feature of concrete mixtures of different composition: the cylinder jacket of Ø 15 × 30 cm mould is perforated according to *Fig. 7.* The granular material mixed with water is poured into the cylinder and compacted on vibrating table. The time of water leakage starting throughout the bore holes can be reproducibly established. The time is expressed in *s* and its symbol is: k_s.

During the investigation it must be taken care of water drops attached to the air bubbles evacuating from concrete due to vibration. The wet bubbles explode in the bore holes and may be mistaken for water. This phenomenon often precedes the continuous leakage of water.

The results reported in the next section derive from the above investigation for determining consistency characterized by water retention capacity (k_s). A vibrating table (type: ÉPGÉP RZ-4) of 50 Hz was used. For comparing values of k_s to the known data, average relationship between k_s and compacting factor (k_{CF}), slump test (k_{sl}) and flow test (k_f) is shown in

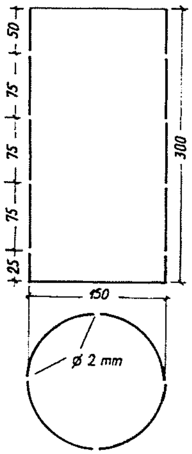

Fig. 7. Perforated cylinder for determining water retention capacity

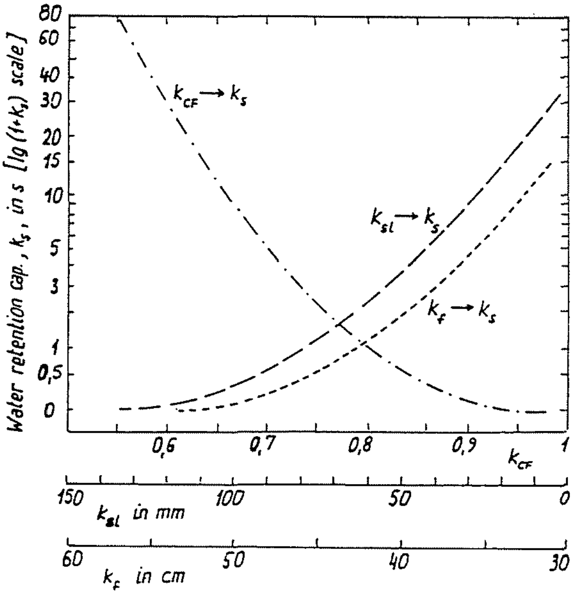

Fig. 8. Average relationship between values of k_s and other index numbers of consistency

Fig. 8. It has to be mentioned that this figure is valid at $m_c \approx 300$ kg/m^3. Other cement contents may produce changes in this relationship.

6. Results of Investigations

Mainly portland cement (type 450) and blast furnace slag portland cement (type 350 kspc 20) were used with river sand and gravel (from Danube). The materials were investigated separately and in mixtures of different compositions ($m_c = 80 - 1600$ kg/m^3). The temperature of mixtures as well as that of setting and hardening concretes was kept at +21 °C ± 3 °C.

6.1. Cement

Specific surface area (S in m^2/kg) of cement was measured by Blaine apparatus. Cement and water were mixed in a paddle mixer of 50 dm^3 for 3 minutes (first water then the cement were added). Consistency was determined by perforated cylinder and compacting factor apparatus (sometimes by slump and flow test) within 8 minutes after adding cement.

Characteristic relationship between the water retention capacity (k_s) and water demand of cement (w_c) can be seen in *Fig. 9* drawn from data of *Table 1.* The signs m'_c and m'_w indicate the data of fully compacted pastes. The relationship can be approximated by exponential function:

$$w_c = 0.3624 \cdot e^{-0.3601 \cdot (0.1 \cdot k_s)^{0.25}} \text{ weight ratio} . \tag{21}$$

The correlation coefficient of this relationship is $r = 0.985$.

Every result of our investigations is shown in *Fig. 10.* The following function complies with the data:

$$w_c = [0.3 + 0.00028 \cdot (S - 100)] \cdot e^{-0.32 \cdot (0.1 \cdot k_s)^{0.27}} \text{ wt} \cdot \text{ratio} \tag{22}$$

where S = specific surface area by Blaine in m^2/kg. The correlation coefficient of relationship in *Fig. 10* for every data is $r = 0.977$.

6.2. Aggregate

Fineness moduli were varied between 3.4 and 7.5; the maximum grain sizes varied between 4 and 32 mm. In several cases, aggregate gradings of the same fineness modulus but different gradation were composed as it can be seen in *Fig. 11.*

Table 1
Results of water demand investigations with
350 kspc 20 (blended cement, 20 pct blast furnace slag)
of Vác (Hungary), $S = 295\ \mathrm{m}^2/\mathrm{kg}$

m'_c	m'_w	w_c	k_s	k_{CF}	k_r	k_{sl}
1847	404	0.219	36	0.61	0	-
1690	455	0.269	3.5	0.74	50	38
1637	472	0.288	2	0.79	90	40
1509	513	0.34	0.1	0.94	125	51
1736	440	0.253	11	0.66	35	34
1808	417	0.231	24	0.63	8	-
1509	513	0.34	0.05	0.93	130	52
1690	455	0.269	4	0.72	60	37
1724	444	0.257	6	0.69	38	54
1635	467	0.282	2	0.75	63	44
1828	411	0.225	30	0.61	-	-
1862	399	0.215	53	0.57	-	-
1779	426	0.24	16	0.63	-	-
1862	399	0.221	48	0.59	-	-
1779	426	0.24	14	0.65	-	-
1690	455	0.269	3	0.75	-	-
1690	455	0.269	4	0.76	-	-
1595	485	0.304	0.8	0.81	-	-
1571	493	0.314	0.1	0.95	-	-
1951	371	0.19	104	-	-	-

Aggregate and water were mixed in laboratory pan mixer of 100 dm^3 (dry aggregate 1 minute, after adding water further 2 minutes). Consistency was measured by perforated cylinder within 8 minutes after adding water. The investigations were carried out from 1973 up to 1994 [19]–[21].

Aggregate gradings shown in *Fig. 12* were used to one part of our investigations [19], its results are summarized in *Table 2.* The water demand is plotted against the water retention capacity; characteristic relationships are shown in *Fig. 13* from data of *Table 2.* The exponential functions fitted to the data are given in *Fig. 13.*

The water demand of aggregates (w_a) is influenced on the one hand by the consistency (k_s) and by the grain shape, size and surface on the other. For developing a single equation valid for every type of aggregate gradings, different characteristics were drawn into calculation (specific surface area, fineness modulus, grain factor, size sum, etc). Without detailing these calculations, it was concluded that fineness modulus gives useful parameter related to k_s for calculating the water demand of aggregate, according to

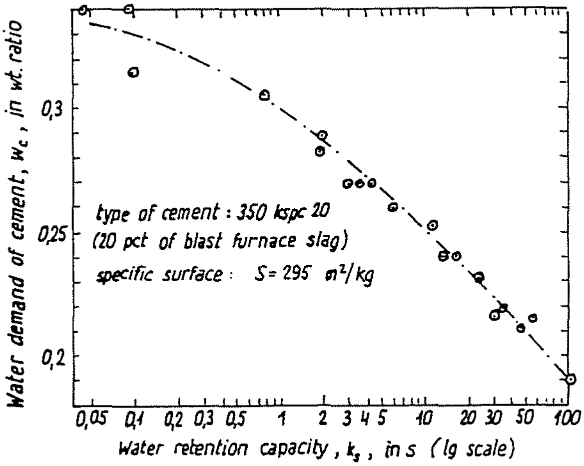

Fig. 9. Relationship between consistency and water demand of cement (type: slag cement, 350 kspc 20)

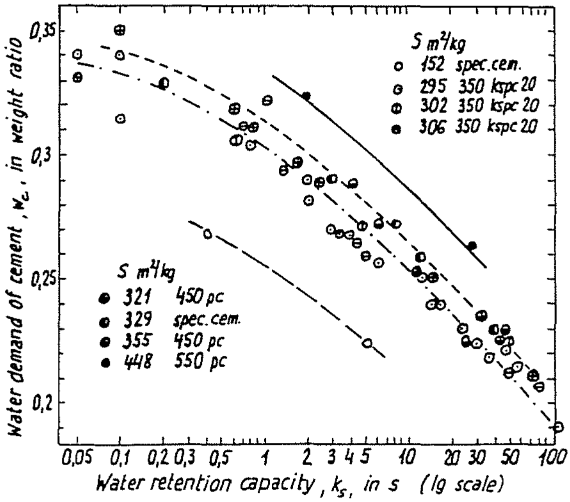

Fig. 10. Relationship between consistency and water demand of cement depending on its specific surface by BLAINE

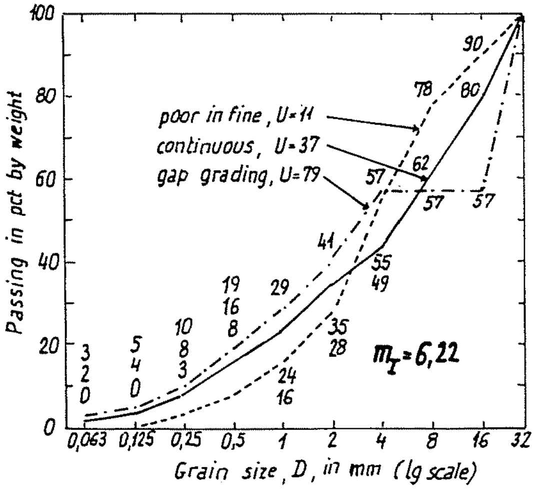

Fig. 11. Gradings with the same fineness modulus but different gradation

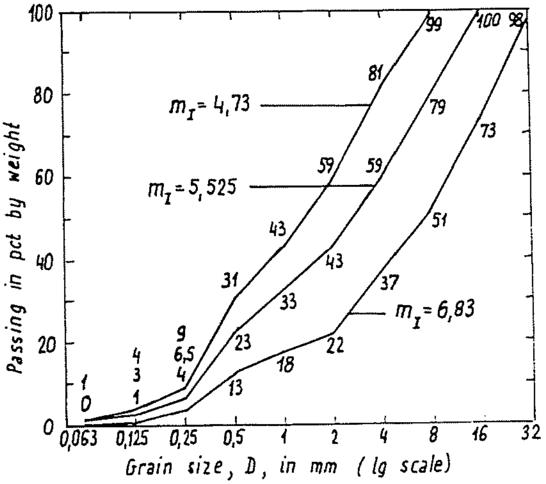

Fig. 12. Gradings used to investigation according to *Table 2*

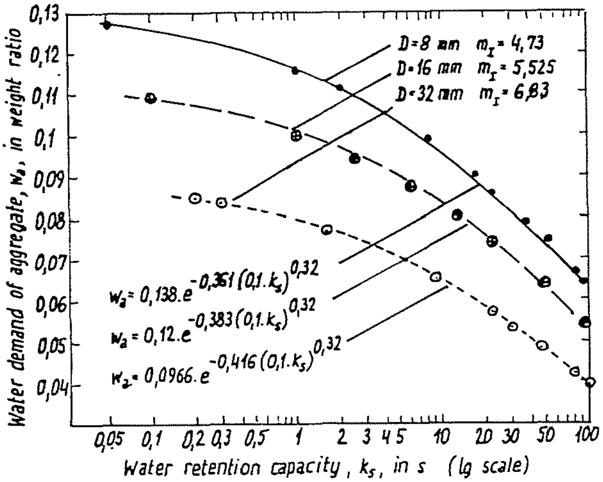

Fig. 13. Relationship between k_s and w_a for given aggregates

the following exponential function:

$$w_a = A \cdot e^{-B \cdot m} \quad \text{weight ratio} \tag{23}$$

where

$$A = 0.3 \cdot e^{-0.22 \cdot (0.1 \cdot k_s)^{0.35}} \tag{24}$$

and

$$B = 0.17 \cdot e^{0.13 \cdot (0.1 \cdot k_s)^{0.32}} \; . \tag{25}$$

Data calculated by (23)–(25) are presented in *Table 2* with w_{ac}. Correlation factor for w_a and w_{ac} values is $r = 0.99$.

6.3. Concrete Mixtures

Concrete mixture composition was changed in wide limits ($m_c = 60 - 1500$ kg/m^3, $k_s = 0 - 60$ s), cement type and aggregate grading varied as earlier. The concretes were mixed in laboratory pan mixer of 100 dm^3 (cement and dry aggregate 1 minute, after adding water 2 minutes). Consistency in perforated cylinder (and sometimes by slump and flow tests as well as by compacting factor apparatus) was measured within 8 minutes after adding water. The investigations were carried out from 1973 to 1994 [19]–[21].

Table 2
Example for water demand investigations of aggregate (sand and gravel from Danube river)

m_a	m_w	w_a	V_l	k_s	w_{ac}
modulus of fineness $m = 4.73$					
1866.7	236.3	0.1266	56.6	0.05	0.12721
1878.4	218.6	0.1164	69.8	1	0.11556
1889.5	203.3	0.1076	81	2	0.11099
1927.1	189.3	0.09825	80.7	8	0.09877
1947.1	180.8	0.09285	81.7	17	0.09009
1951.7	164.4	0.08422	96.3	23	0.08619
1941.8	153.5	0.07905	111	38	0.07915
1938.5	146.2	0.07542	119.5	51	0.07472
1944.5	134.7	0.06929	128.7	82	0.06714
1939.1	125.4	0.06465	140.1	97	0.06434
modulus of fineness $m = 5.525$					
1958.2	220.5	0.1126	37.8	0.1	0.1091
1968.1	199.7	0.1049	54.8	1	0.10008
1975.4	189.1	0.09576	63	2.5	0.09439
2021.8	173	0.08555	61.2	6	0.08744
2042	163.8	0.08023	62.7	12	0.08074
2062.1	149.6	0.07254	69.3	22	0.07396
2056.8	136.4	0.0663	84.5	50	0.06459
2044.8	127	0.06219	99.6	50	0.06459
2036.2	113.8	0,05587	114.9	92	0.0547
modulus of fineness $m = 6.83$					
2058.1	180.7	0.08782	39.7	0.2	0.08501
2070.7	170.5	0.08236	45.1	0.3	0.08376
2088.4	157.3	0.07534	51.6	1.5	0.07703
2151.4	139	0.06461	46.1	9	0.06505
2186	127.8	0.05847	44.2	21	0.05736
2203.8	115	0.0522	50.2	30	0.05348
2196.2	103.1	0.04732	64.2	48	0.0486
2182.7	95.1	0.04357	78.1	80	0.04265
2188.6	89.1	0.04073	81.8	101	0.03984

At the first part of research work, mixtures with cement content $m_c = 100 - 500$ kg/m^3 and constant water content were made. Characteristic results are shown in *Table 3*, where blended cement (350 kspc 20) was used with specific surface area $S = 295$ m^2/kg, aggregate fineness modulus $m = 4.73$ (grading can be seen in *Fig. 12*). The water content calculated by (23) was kept constant.

The water retention capacity (k_s) is plotted against cement content in *Fig. 14*, where it can be found that concretes made with constant water

Table 3
Results of concrete mixtures
($m_c = 100 - 500$ kg/m^3, constant water content)

m'_c	m'_w	m'_a	V_1	k_s	m'_c	m'_w	m'_a	V_1	k_s
98	223	1870	37.1	0.4	100	201	1903	45.9	3
125	223	1872	27.4	0.5	127	200	1900	38.9	5
187	223	1865	10.8	0.4	191	201	1905	16.1	4
208	223	1870	1.5	0.5	212	201	1907	8.1	3
232	222	1858	0	0.5	239	201	1905	0.9	4
260	223	1829	0	0.7	260	201	1888	0	6
300	223	1795	0	0.9	300	201	1854	0	6
400	223	1710	0	3	400	201	1769	0	9
500	223	1625	0	4	500	201	1684	0	16
102	187	1941	44.8	9	104	163	1975	55.5	27
129	187	1935	38.8	8	132	163	1978	44.8	31
194	187	1939	16.2	10	197	163	1971	27	26
215	186	1934	12	9	220	163	1975	17.9	30
242	187	1937	1.4	9	247	163	1979	7.2	31
300	187	1891	0	13	300	163	1953	0	34
400	187	1806	0	18	400	163	1868	0	41
500	187	1721	0	26	500	163	1783	0	56

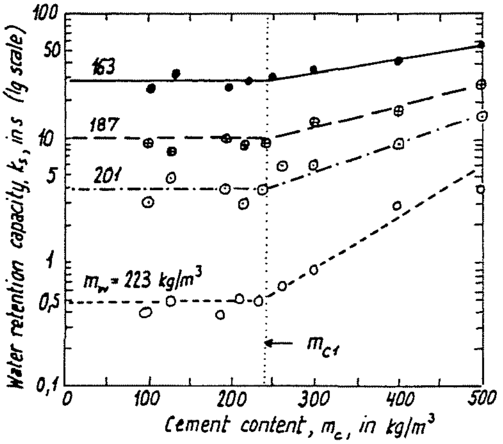

Fig. 14. Relationship between water retention capacity and cement content at constant water contents

content according to the aggregate water demand have the same consistency (k_s) up to $m_c \approx 240 - 250$ kg/m^3 at fineness modulus $m = 4.73$.

Without giving details, the following has to be noted: it could be stated from the investigation with other gradings and cement types that concretes mixed with water content according to aggregate water demand have the same consistency in different cement content limits: the higher the fineness modulus the lower the upper limit of cement content is (e.g. for $m = 5.525$ see *Fig. 12*, $m_c \approx 220 - 230$ kg/m^3; for $m = 6.83$ $m_c \approx 190 - 200$ kg/m^3).

At the second part of investigations, mixtures were made with cement contents between upper limit of that found at first part and $m_c =$ 500 kg/m^3, furthermore with varying water content. Characteristic results are shown in *Table 4*, where the cement and aggregate were the same as in *Table 3*. The water content of concrete (m_w) is plotted against cement content (m_c) in *Fig. 15*, where water retention capacities (k_s) and differences between water content (m_w) and aggregate water demand (m_{wo}) are also indicated. It can be seen that the water surplus ($m_w - m_{wo}$) depends on consistency: the wetter the concrete the more the water surplus additional needed for the same consistency.

Table 4

Results of concrete mixtures

($m_c = 230 - 500$ kg/m^3, varying water content)

m'_c	m'_w	m'_a	V_1	k_s	m'_c	m'_w	m'_a	V_1	k_s
232	222	1858	0	0.5	239	201	1905	0.9	4
260	224	1826	0	0.4	260	202	1886	0	5
300	228	1782	0	0.5	300	205	1842	0	4
400	238	1672	0	0.5	400	214	1734	0	3
500	247	1561	0	0.4	500	223	1626	0	4
242	187	1937	1.4	9	247	163	1979	7.2	31
260	188	1923	0	10	260	165	1979	2	30
300	191	1880	0	11	300	168	1942	0	30
400	200	1773	0	10	400	176	1836	0	29
500	208	1665	0	10	500	183	1731	0	30

At the third part of investigations, mixtures were made with cement contents between $m_c = 500$ kg/m^3 and that of the cement paste, and varying water content. Characteristic results are shown in *Table 5*, where cement and aggregate were the same as in *Table 3*. The data were plotted similarly in *Fig. 16* to *Fig. 14*.

It has to be noted that in this section some selected results are summarized only. Detailed results can be found in ÉTI Reports [19] – [21].

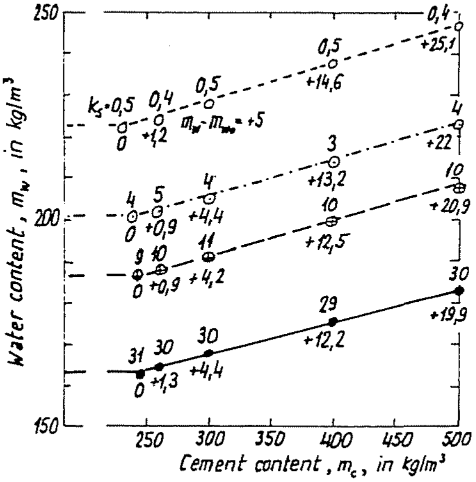

Fig. 15. Necessary water content to the same consistency at varying cement content ($m_c \leq 500$ kg/m^3)

Table 5

Results of concrete mixtures

($m_c = 500$ kg/m^3, varying water content)

m'_c	m'_w	m'_a	V_1	k_s	m'_c	m'_w	m'_a	V_1	k_s
500	247	1561	0	0.4	500	223	1626	0	4
600	257	1451	0	0.5	600	232	1517	0	4
700	266	1341	0	0.5	700	240	1409	0	5
800	285	1208	0	0.4	800	256	1283	0	4
1000	334	908	0	0.5	1000	301	995	0	5
1300	407	457	0	0.6	1300	367	564	0	4
1605	482	0	0	0.5	1692	454	0	0	4
500	208	1665	0	10	500	183	1731	0	30
600	216	1558	0	9	600	191	1625	0	30
700	225	1451	0	11	700	199	1519	0	28
800	239	1327	0	12	800	214	1393	0	31
1000	277	1057	0	12	1000	252	1123	0	33
1300	337	642	0	11	1300	309	717	0	31
1747	437	0	0	10	1831	410	0	0	31

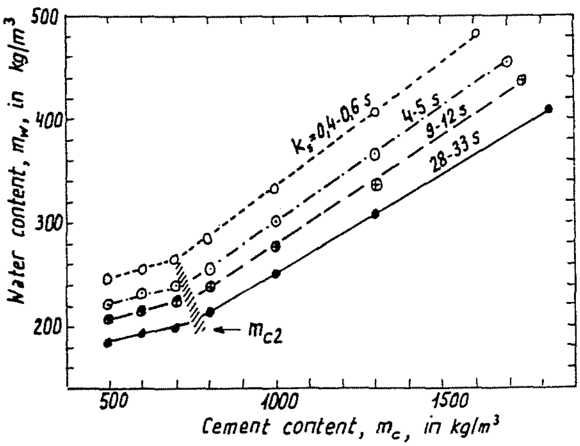

Fig. 16. Necessary water content to the same consistency at varying cement content ($m_c \geq 500$ kg/m^3)

7. Evaluation of Results, Discussion

The results presented up to this point demonstrate that water demand of concrete for a given consistency can be calculated and determined, respectively, as follows:

(1) Water content of water+aggregate mixture can be calculated as

$$m_{wo} = m_{ao} \cdot w_a \text{ kg/m}^3 \,, \tag{26}$$

where m_{ao} is the weight of aggregate compacted in 1 m^3 volume at water content m_{wo} (the investigation as well as calculation of this aggregate weight – so called standard aggregate weight – is discussed in [22]). Water demand of aggregate can be investigated with a simple apparatus shown in *Fig. 7* and calculated from *Eq.* (23).

(2) Water content m_{wo} gives the required consistency for concretes having less or equal cement contents than m_{c1}. The value m_{c1} depends on aggregate properties and consistency (see *Fig. 14*).

(3) Water demand of cement w_c can be investigated by the same apparatus as that of aggregate (*Fig. 7*) and calculated from *Eq.* (22). Paste composition (m_{cp} and m_{wp}) is calculated from *Eqs.* (16) and (17).

(4) Three points of relationship between water content of concretes with given consistency and its cement content are obtained from above calculations (or investigations) as it is shown in *Fig. 17.* These points

are: m_{wo} at $m_c = 0$ and m_{c1} as well as m_{wp} at m_{cp} (*Fig. 17/a*). They determine two connecting lines: line between $m_c = 0$ and m_{wp} at m_{cp} as well as line between m_{wo} at m_{c1} and m_{wp} at m_{cp} as it can be seen in *Fig. 17/b*.

Lines shown in *Fig. 17/b* determine **three characteristic cement contents**:

(a) m_{c1}: between $m_c = 0$ and m_{c1} water content in mixtures of a given consistency is constant;

(b) m_{c2}: cement content belonging to the intersection of horizontal line m_{wo} and connecting line of $m_c = 0$ and m_{wp} at m_{cp}. As the latter has a function:

$$m_w = m_c \cdot w_c \ \text{kg/m}^3 \ , \tag{27}$$

and for intersection is valid that $m_{wo} = m_{c2} \cdot w_c$, therefore

$$m_{c2} = m_{wo} : w_c \ \text{kg/m}^3 \ . \tag{28}$$

According to the investigations [19]–[22]:

$$m_{c1} = m_{c2} : 3 \ \text{kg/m}^3 \ . \tag{29}$$

(c) m_{cp}: cement content of paste according to (16)

On *Fig. 17/b* **two characteristic water contents** be determined:

(I) m_{wo}: aggregate water content according to (26) and

(II) m_{wp}: cement paste water content according to (17) at the same consistency.

On *Fig. 17/b* **two characteristic differences** can be found:

$$\Delta m_w = m_{wp} - m_{wo} \ \text{kg/m}^3 \ , \tag{30}$$

$$\Delta m_c = m_{wp} - m_{c1} \ \text{kg/m}^3 \ . \tag{31}$$

Equation of line connecting m_{wo} at m_{c1} and m_{wp} at m_{cp} is as follows:

$$m_w = m_{wo} + (m_c - m_{c1}) \frac{\Delta m_w}{\Delta m_c} \ \text{kg/m}^3 \ . \tag{32}$$

(5) The necessary water content of concrete for a required consistency can be expressed by a power function going between lines (27) and (32). The curve of function is indicated with a dotted one in *Fig. 17/b*. This curve is replaceable with two lines according to *Fig. 17/c*, therefore

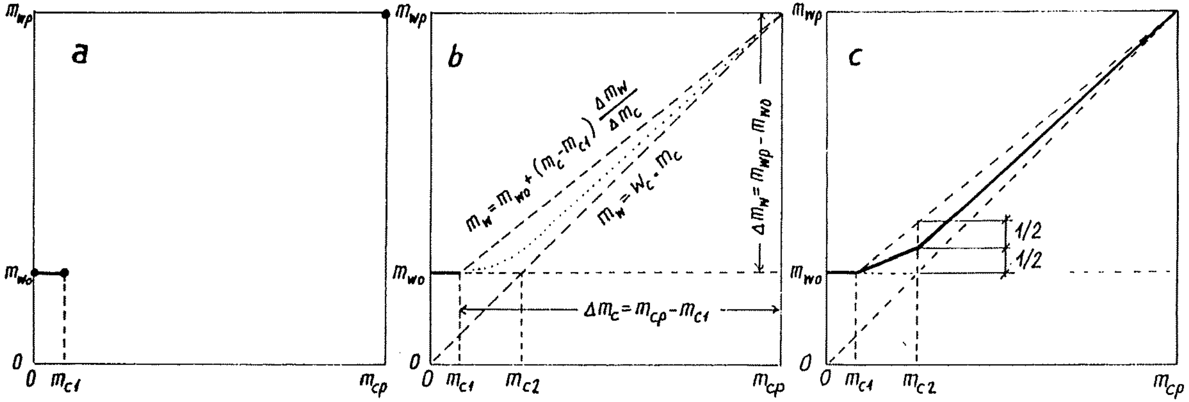

Fig. 17. Variation of water content in concretes of the same consistency depending on cement content

the required water content for a given consistency can be calculated from the following equations:
when

$$m_c \leq m_{c1}: \qquad m_w = m_{wo} \text{ kg/m}^3 \tag{33}$$

when

$$m_{c1} < m_c \leq m_{c2}$$

$$m_w = m_{wo} + \frac{(\Delta m_w : \Delta m_c) \cdot (m_c - m_{c1})}{2} \text{ kg/m}^3 \tag{34}$$

when

$$m_{c2} > m_c:$$

$$m_w = m_{wo} + \frac{(\Delta m_w : \Delta m_c) \cdot (m_c - m_{c1}) + (m_c w_c - m_{wo})}{2} \text{ kg/m}^3 . \tag{35}$$

Concretes for special purposes (e.g. impermeable concrete, resistance to abrasion or aggressive solutions, freeze thaw resistance) need specified low water cement ratios. Concrete composition with specified water cement ratio and consistency can be determined from the following equations:
when

$$m_c \leq m_{c1}: \qquad m_c = m_{wo} : x \quad \text{and} \quad m_w = m_{wo} \text{ kg/m}^3 \tag{36}$$

when

$$m_{c1} < m_c \leq m_{c2}: \qquad m_c = \frac{m_{wo} - (\Delta m_w : 2\Delta m_c) \cdot m_{c1}}{x - (\Delta m_w : 2\Delta m_c)}$$

$$\text{and} \quad m_w = x \cdot m_c \text{ kg/m}^3 \tag{37}$$

when

$$m_{c2} > m_c: \qquad m_c = \frac{m_{wo} - (\Delta m_w : 2\Delta m_c) \cdot m_{c1}}{2x - [w_c + (\Delta m_w : \Delta m_c)]}$$

$$\text{and} \quad m_w = x \cdot m_c \text{ kg/m}^3 \tag{38}$$

Summary

Investigations were made during the past two decades to create a method for calculating water quantity necessary for a required concrete consistency. It was assumed that

(1) the water demand of aggregate and that of cement can be separately investigated

(2) if suitable method can be found to test consistency not only of concrete and cement paste, but also that of aggregate+water mixture.

Such a simple device was created according to *Fig. 7*, which measures in secundum the water retention capacity of concrete ingredients and mixtures. This characteristic was designated as k_s.

The experiments proved that the necessary water quantity depends on fineness modulus of aggregate and specific surface area of cement on the one part and on cement content of concrete on the other. More specifically, there are three sections of cement content controlling the necessary water quantity:

(a) if $m_c \leq m_{c1}$, the water quantity depends only on aggregate properties;

(b) if $m_{c1} < m_c \leq m_{c2}$, the water quantity depends mainly on aggregate properties and in less degree on that of cement;

(c) if $m_c > m_{c2}$, the water quantity depends mainly on cement properties and in less degree on that of aggregate.

Values of m_{c1} and m_{c2} can be calculated from water demand of cement and from that of aggregate.

On the basis of investigations, formulas were developed for calculation of water demand both for varying cement content and varying water–cement ratio.

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