Static indentation hardness testing of concrete: a long established method revived

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Hardness (even in-situ) testing of materials offers the potential of strength estimation by means of a much simpler test than the direct compressive or tensile strength testing. Nevertheless, the theoretical approaches of contact mechanics and hence that of hardness has several gaps. In the technical literature limited number of experimental studies is available on cement mortars and concretes by static ball indentation hardness testing devices. It can be found that a power function can suitably characterize the relationship between the Brinell hardness and the compressive strength of concrete in those cases where one load level is applied for testing. A much detailed analysis can be provided if several load levels are used. Power functions between the indenter load (F) and the residual impression diameter (d) can be formulated for different concrete strengths, $F \propto a \times d^n$, of those empirical parameters *a* and *n* are material properties as it was demonstrated for metals by Meyer in 1908. Objective of present experimental study was to thoroughly investigate normal weight hardened concrete specimens by a static ball indentation hardness testing laboratory device at several load levels on a wide range of compressive strength and age of concrete at testing. It was found that the power in the Meyer relationship is apparently a constant for concrete, independently of the water-cement ratio and the age at testing, while the multiplier in the Meyer relationship is very sensitive to both influencing factors. The results disproved the hypothesis of the power function relationship between the residual indentation diameter and the compressive strength of concrete with a power of -4.0 published in the technical literature. The results confirmed the existence of a linear general model for the relationship between the compressive strength and the Brinell hardness of concrete, as an average power of 1.128 was found.

Keywords: concrete, compressive strength, Brinell hardness, Meyer hardness, indentation testing

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1. Introduction

Hardness testing was the first material testing practice from the 1600's in geology and engineering through the scratching hardness testing methods (1640, Barba; 1722, Réaumur; 1768, Kvist; 1801, Haüy; 1812, Mohs); appearing much earlier than the systematic material testing that is considered to be started in 1857 when David Kirkaldy, Scottish engineer set up the first material testing laboratory in London, Southwark [1, 2, 3, 4, 5]. The theoretical hardness research was initialized by the pioneering work of Heinrich Hertz in the 1880's [6]. Hertz's proposal formed also the basis of the indentation hardness testing methods by Brinell (1900), Rockwell (1920), Vickers (1924) and Knoop (1934) [7]. These conventional methods involve in different ways the measurement of the size of a residual plastic deformation impression in the tested specimen as a function of the indenter load. Amongst several different indenter geometries the spherical indenters can be used for testing both ductile materials (e.g. metals) and brittle materials (e.g. ceramics). The response of materials to the indentation test includes elastic (reversible) and plastic (irreversible) deformations as well as forming of cone cracks in brittle materials; therefore, the definition of the term 'hardness' is not evident.

The scientific definition of hardness has been of considerable interest from the very beginning of hardness testing, however, still today – more than 100 years after Hertz's original proposal – no absolute definition of hardness is available in material sciences. According to Hertz, hardness is the least value of pressure beneath a spherical indenter necessary to produce a permanent set at the centre of the area of contact. As Hertz's criterion has some practical difficulties, the hardness values defined by the practical methods are usually indicating various different relationships between the indenter load and the tested specimen's resistance to penetration or permanent deformation.

Fig. 1.a. schematically indicates the deformation field of an elastic-plastic medium under a spherical indenter during static indentation hardness testing. A hemispherical, incompressible core of material can be considered directly beneath the indenter, being in hydrostatic stress field [8]. Surrounding the core there is a hemispherical plastic zone that connects the elastically strained material. The schematic load-deflection curve (compliance curve) is given in *Fig. 1.b*. The residual plastic deformation impression (h_r) can be measured and used for the calculation of hardness after unloading the indenter. It can be realized that the residual plastic deformation impression is a result of a three-dimensional, constrained deformation field that is strongly affected by the testing method itself (e.g. the indenter can be a sphere, cone, pyramid, diamond etc.). In case of ductile materials the plastic deformation is considered to be started when the mean contact pressure is $p_m = F/a^2\pi \approx 1.1f_y$ (where f_y is the uniaxial yield stress of the material and the contact radius (a) can be predicted from Hertz's proposal; $a \propto F^{2/3}$). Plastic deformation exists beneath the surface at higher loads and constrained by the surrounding elastically strained material. With further loading the plastic deformation extends to the surface of the specimen as the mean contact pressure is

$p_m = F/a^2\pi \approx 2.8f_y$ and continues to grow in size but the mean contact pressure is not increasing any more (the contact radius (a) can be predicted to be linearly increasing by loading; $a \propto F$) [9]. Cone cracks are forming at the contact surface in the case of elastic-brittle materials, however, plastic deformations can be also realized due to the local densification through e.g. phase change of the material as a result of high compressive stresses (which deformation is considerably different in nature from the plastic yield of ductile materials) [7].

Nevertheless, the theoretical approaches of contact mechanics and hence that of hardness has several gaps, the hardness (even in-situ) testing of materials offers the potential of strength estimation by means of a much simpler test than the direct compressive or tensile strength testing. This is the reason why several different hardness testers became available for material testing and the research on hardness of materials has been very dynamic from the beginning up to present day.

2. Significance and objectives of present studies

Hardness testing practice of cementitious materials – such as concrete – exclusively applies nowadays the dynamic rebound surface hardness testing devices (e.g. the Schmidt rebound hammer), rather than devices of plastic indentation hardness testing methods. Rebound hammers can be used very easily and the measure of hardness (i.e. the rebound index) can be read directly on the display of the testing devices. However, the impact energy of the rebound hammers usually can not be adjusted by the operator, thus the material response available by rebound hammer testing can provide only limited information. Also, the rebound hammers give information about the elastic and damping properties of the very surface layer of concrete that can not be necessarily related directly to the strength of concrete.

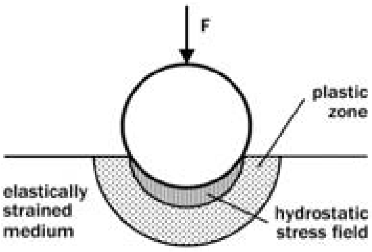

Fig. 1.a. Deformation field of an elastic-plastic medium under a spherical indenter during static indentation hardness testing
1.a. ábra Rugalmas-képlékeny közeg alakváltozási mezője gömb alakú szúrószerszám alatt, statikus keménység vizsgálat során

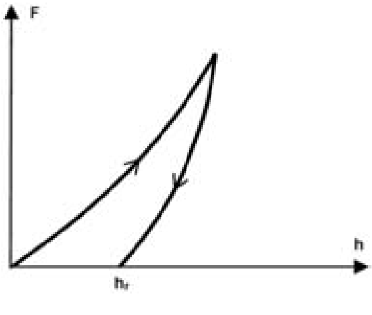

Fig. 1.b. Schematic load-deflection curve (compliance curve) during static indentation hardness testing
1.b. ábra Sematikus terhelés-tehermentesítési görbe a statikus keménység vizsgálat során

It was also demonstrated recently that the analysis of rebound hammer test data and strength estimation need special considerations for which purpose no general theory was available until now [10].

Objectives of present experimental studies were on one hand to thoroughly investigate normal weight hardened concrete specimens by a static ball indentation hardness testing laboratory device on a wide range of compressive strength and age of concrete at testing; and on the other hand, to compare measured data with rebound hardness results as well as Young's modulus and compressive strength values of the same concretes. The main purpose of the studies is to provide experimental evidence – if any – between the relationship of static and dynamic hardness values for concretes as well as compressive strength and elastic properties to be able to support the better understanding of hardness of porous solid materials. Present paper intends to give a summary about the static ball indentation hardness results.

3. Previous studies

In the 1920's and in the 1930's limited number of researchers investigated cement mortars and concretes by the Brinell method or similar developments of static ball indentation hardness testing devices [11, 12, 13, 14, 15] and later the research in the field become even less frequent [16]. Some studies applied only one or two load levels and tried to find a relationship between the Brinell hardness and the compressive strength of concrete or between the residual plastic deformation impression and the compressive strength of concrete, while other studies applied several load levels and took a wider look on the topic.

In the representation of the test results several different relationships can be formulated. The compressive strength can be represented as a function of the Brinell hardness (*Fig. 2.a.*) or the residual impression diameter (*Fig. 2.b.*) in those cases where one load level is applied for testing. It can be found that a power function can suitably characterize the relationship between the Brinell hardness and the compressive strength of concrete, $f_c \propto a \times HB^m$ (with a power of $m \approx 2$) [15]. The relationship between the residual impression diameter (d) and the compressive strength of concrete can be characterized by a logarithm function, $\log f_c \propto a_1 - a_2 \times d$ [12, 13, 14]. A much detailed analysis can be provided if several load levels are used (*Fig. 2.c.*). Power functions between the indenter load (F) and the residual impression diameter (d) can be formulated for different concrete strengths, $F \propto a \times d^n$, of those empirical parameters *a* and *n* are material properties as it was demonstrated for metals by Meyer in 1908 [17].

It was also indicated for metals that the Brinell hardness, HB and the Meyer hardness, HM (see appendix) are not load-independent measures, therefore they can not necessarily provide a reliable estimation for the strength if the load level of the indentation test is not chosen correctly [18].

Much more accurate parameters are – however, attained in a more complicated way – the empirical constants of the Meyer power functions that can be considered to be material properties [17]. *Fig. 3.a–3.c* are prepared based on Meyer's published data to demonstrate this behaviour for different metals.

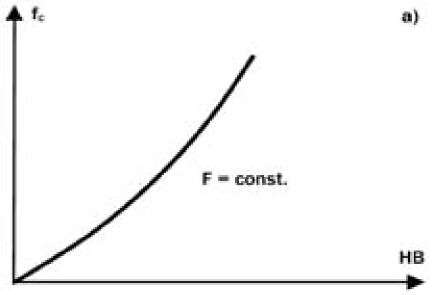

Fig. 2.a. Relationship between the compressive strength (f_c) and the Brinell hardness (HB) of concrete
2.a. ábra A beton nyomószilárdsága (f_c) és Brinell keménysége (HB) közötti összefüggés

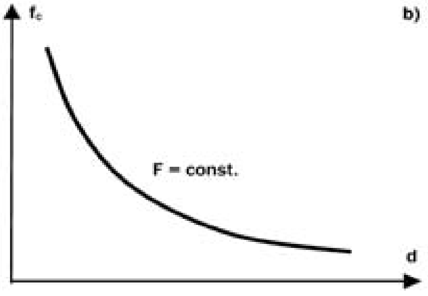

Fig. 2.b. Relationship between the compressive strength (f_c) and the residual impression diameter (d) of concrete
2.b. ábra A beton nyomószilárdsága (f_c) és maradó golyónyom átmérője (d) közötti összefüggés

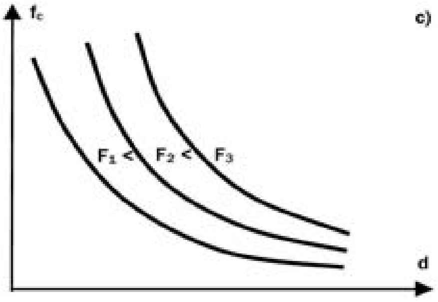

Fig. 2.c. Relationship between the compressive strength (f_c) and the residual impression diameter (d) of concrete at several load levels
2.c. ábra A beton nyomószilárdsága (f_c) és a maradó golyónyom átmérője (d) közötti összefüggés több teherszint alkalmazása esetén

Based on the review of the available information in the technical literature in the field of static ball indentation hardness testing of concrete one can realize that researchers did not publish results that can be suitable for practical use and the theoretical analysis of the hardness of cementitious porous solids is also not provided. It can be also mentioned that no data are available concerning the relationship between static and dynamic hardness of cementitious porous solids.

4. Testing method

An experimental programme was completed on a wide range of compressive strength of normal weight concretes in the Budapest University of Technology and Economics (BME), Department of Construction Materials and Engineering Geology, to study the static indentation hardness behaviour.

Concrete was mixed from Danube sand and gravel using CEM I 42.5 N cement with w/c ratios of 0.40, 0.50 and 0.65. Consistency of the tested concrete mixes was 500±20 mm flow. Design air content of the compacted fresh concretes was 1.0 V%.

The specimens were cast into steel formworks and the compaction of concrete was carried out by a vibrating table. The specimens were stored under water for 7 days as curing. After 7 days the specimens were stored at laboratory condition (i.e. 20±3 °C temperature and 65±5% relative humidity). Tests were performed at the age of 3, 7, 14, 28, 56, 90 and 240 days. 150 mm cube specimens and 120×120×360 mm prism specimens were prepared for the experiments.

Static indentation tests were carried out by a Brinell testing device with ball diameter of 10 mm. Testing loads of 187.5 kg to 3000 kg were applied for 30 seconds on the concrete surfaces.

F, kN	$f_c = a \cdot d^{-n}$	R^2	$f_c = a \cdot HB^m$	R^2
2.5	$f_c = 672.9 \cdot d^{-2.346}$	0.741	$f_c = 0.885 \cdot HB^{1.146}$	0.743
5.0	$f_c = 2384.0 \cdot d^{-2.844}$	0.800	$f_c = 0.324 \cdot HB^{1.363}$	0.803
7.5	$f_c = 4783.7 \cdot d^{-2.949}$	0.918	$f_c = 0.314 \cdot HB^{1.369}$	0.922
10.0	$f_c = 2532.3 \cdot d^{-2.381}$	0.774	$f_c = 0.824 \cdot HB^{1.089}$	0.777
15.0	$f_c = 2651.0 \cdot d^{-2.156}$	0.741	$f_c = 1.368 \cdot HB^{0.960}$	0.739
17.5	$f_c = 3058.3 \cdot d^{-2.122}$	0.775	$f_c = 1.721 \cdot HB^{0.916}$	0.771
20.0	$f_c = 2008.6 \cdot d^{-1.804}$	0.704	$f_c = 1.001 \cdot HB^{1.055}$	0.788

Table 1. Regression curve (power function) parameters
1. táblázat A regressziós görbék (hatványfüggvények) paraméterei

Five individual tests were carried out at each load level and five residual impressions were prepared. Diameters of the residual impressions were measured by a hand microscope of 8× magnification. Further increase of loading was stopped when the formation of cone cracking was observed to be governing during loading.

Compressive strength on the cube specimens, Young's modulus on the prism specimens and carbonation depths were also recorded at the age of 3, 7, 14, 28, 56, 90 and 240 days.

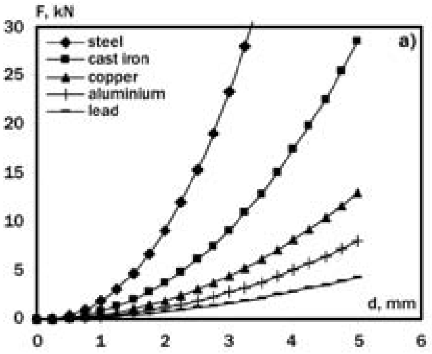

Fig. 3.a. Meyer power functions between the indenter load (F) and the residual impression diameter (d) for different metals [17]
3.a. ábra Különböző fémek Meyer-féle hatványtörvénye (a terhelő erő és a maradó golyónyom átmérője közötti összefüggés) [17]

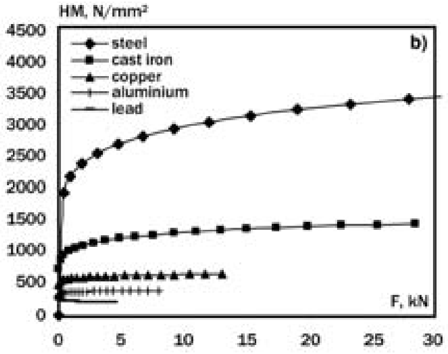

Fig. 3.b. Relationships between the Meyer hardness (HM) and the indenter load (F) for different metals [17]
3.b. ábra Különböző fémek Meyer keménysége és a terhelő erő közötti összefüggés [17]

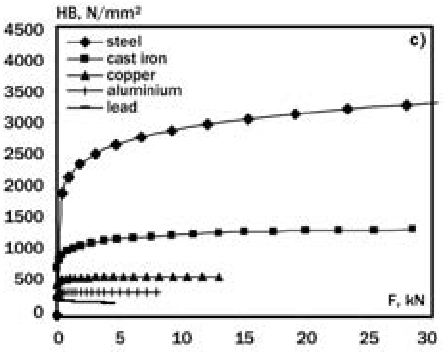

Fig. 3.c. Relationships between the Brinell hardness (HB) and the indenter load (F) for different metals [17]
3.c. ábra Különböző fémek Brinell keménysége és a terhelő erő közötti összefüggés [17]

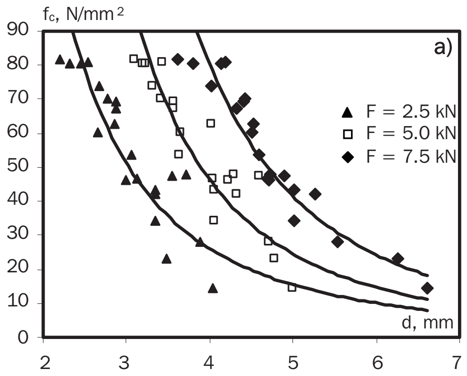

Fig. 4.a. Relationship between the compressive strength (f_c) and the residual impression diameter of concrete at different load levels

4.a. ábra A beton nyomószilárdsága (f_c) és a maradó golyónyom átmérője (d) közötti összefüggés különböző teherszintek alkalmazása esetén

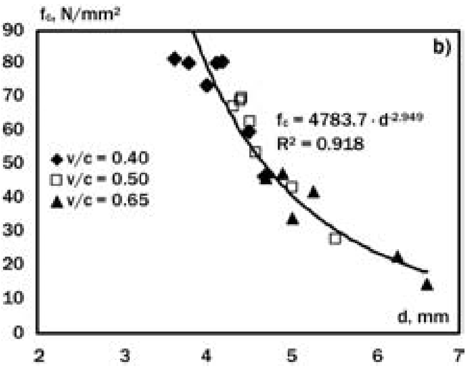

Fig. 4.b. Relationship between the compressive strength (f_c) and the residual impression diameter (d) of concrete at the load level of F = 7.5 kN (data are separated according to the applied three water-cement ratio)

4.b. ábra A beton nyomószilárdsága (f_c) és a maradó golyónyom átmérője (d) közötti összefüggés F = 7,5 kN teherszint alkalmazása esetén (az adatokat a víz-cement tényező alapján elkülönítve ábrázoltuk)

5. Results

The correlation between the concrete compressive strength and the residual indentation diameter is indicated in *Fig. 4.a.* for different load levels. It can be realized that power functions can characterize reasonably well the responses (correlation coefficients are in the range of r^2 = 0.70 to 0.92). Regression curve parameters are resulted in *Table 1*. For the load level of F = 7.5 kN results are separated according to the applied three water-cement ratio in *Fig. 4.b*.

The Meyer power functions for specimens of the three applied w/c are indicated in *Fig. 5.* represented for three different ages at testing: at the age of 7 days (*Fig. 5.a.*), 28 days (*Fig. 5.b.*) and 240 days (*Fig. 5.c.*). It can be studied that the Meyer power functions sensitively follow the strength development in time and the empirical constants have a tendency of change in time. The Meyer parameters found in present experimental programme are represented in *Fig 6.* as a function of time (*Fig. 6.a.*) and of water-cement ratio (*Fig. 6.b.*). It can be seen that the power in the Meyer relationships is apparently a constant for concrete, independently of the water-cement ratio and the age at testing, while the multiplier in the Meyer relationships is very sensitive to both influencing factors.

Brinell hardness, HB results are plotted in *Fig. 7.* against the concrete compressive strength and an apparent linear relationship can be seen between compressive strength and Brinell hardness, HB of concrete. Results are not separated in the representation either by water-cement ratio or testing load to be able to study a possible general behaviour pattern. Regression curve parameters available for the applied load levels are summarized in *Table 1*.

Fig. 8.a. indicates Brinell hardness, HB results in time for specimens of w/c = 0.50 represented as a function of the testing load. It can be studied that an apparent peak hardness is showing on each response. The same behavioural scheme was realized for the Meyer hardness, HM results. If the hardness values are represented as a function of the residual indentation diameter then the same increasing-decreasing tendencies are resulted (*Fig. 8.b.*). It is possible to read the peak hardness values on each regression curve. The peak hardness readings are plotted in *Fig. 9.* against the compressive strength and an apparently linear relationship is resulted.

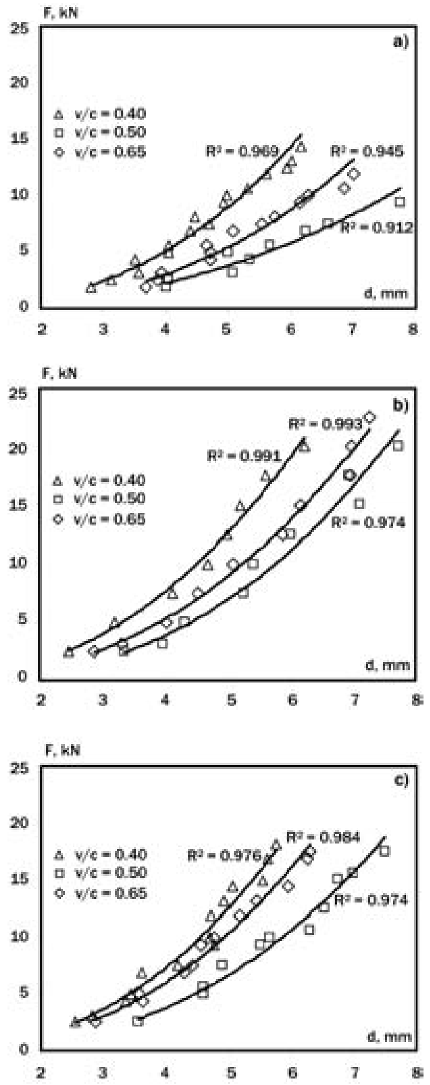

Fig. 5. The Meyer power functions for specimens of w/c = 0.40, 0.50 and 0.65 a) at the age of 7 days; b) at the age of 28 days; c) at the age of 240 days

5. ábra v/c = 0,40; 0,50 és 0,60 víz-cement tényezőjű próbatestek Meyer-féle hatványtörvénye a) 7 napos korban; b) 28 napos korban; c) 240 napos korban

6. Discussion

The technical literature indicates that the Meyer hardness, HM can be used as a simplifying estimate of the Brinell hardness, HB when the residual indentation diameter (d) is $0.3 \leq d/D \leq 0.7$ (where D is the diameter of the ball indenter) [19, 20]. Results of *Fig. 4.*, *Fig. 7.* and *Table 1.* confirm the interchangeability of the two hardness parameters: if one expresses the Brinell hardness, HB as a function of the residual indentation diameter from the experimental data then a power function for the residual indentation diameter is resulted with a power of about -2.0 (the same as characterizes Meyer hardness, HM; see Appendix). In our experiments the power was found to be equal to -2.106 as an average. Technical literature confirms our results: an analysis of the experimental data published by Gaede (1957) has resulted a power of -2.187 as an average [21].

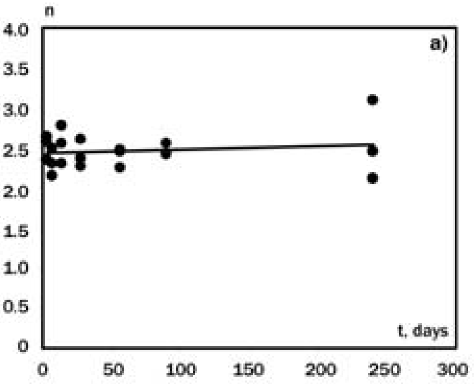

Fig. 6.a. The power of the Meyer function as a function of time
6.a. ábra A Meyer-féle hatványtörvény kitevője az idő függvényében

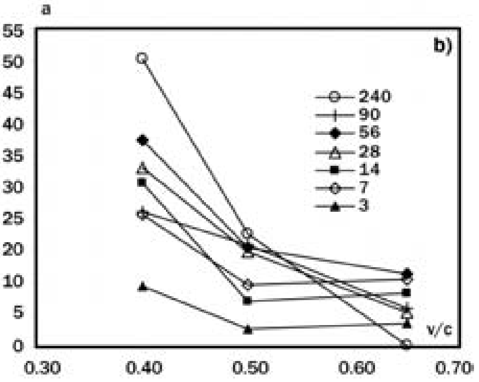

Fig. 6.b. The multiplier of the Meyer function as a function of time
6.b. ábra A Meyer-féle hatványtörvény szorzója az idő függvényében

The technical literature also indicates that the relationship between the residual indentation diameter and the compressive strength is a power function with a power of -4.0 (based on simplified analysis) [19, 20]. Our experimental results do not confirm this hypothesis.

The power values can be studied in *Table 1.* Average value of -2.372 can be considered to be valid for present experiments.

Technical literature confirms our results: after a rigorous analysis of the paper of Kolek (1958) it was realized that the linear regression was carried out inaccurately in the paper and the accurate value of the power is -2.584 rather than -4.0 indicated originally [19].

It can be found in the technical literature that a linear response can model the relationship between the compressive strength and the Brinell hardness, HB of concrete [22]. The results of *Fig. 7.*, *Fig. 9.* and *Table 1.* confirm this supposition. In present experiments an average power of 1.128 was found.

The observations of *Fig. 8.a.* and *Fig. 8.b.* are very special and no similar findings were published earlier in the technical literature. However, the observed performance clearly illustrate the elastic-plastic behaviour of concrete under the ball indenter as well as the mechanism of local densification and the formation of cone cracking.

The mechanisms are summarized as follows. At lower loads no full plastic response of the concrete can be developed and the densification under the ball indenter is not pronounced. Increasing load results increasing hardness values. At higher loads the local collapsing of the capillary walls in the hardened cement paste and the local micro-crushing of small aggregate particles near the contact area results more pronounced densification; that can be realized in an apparent peak hardness when full plastic response of the concrete is utilized.

As load is further increased the formation of cone cracks is started at the contact surface (always clearly visible during testing) and the softening of the cracked concrete is realized in the apparent decreasing hardness values. The same behavioural scheme can be studied if one represents the Meyer hardness, HM instead of the Brinell hardness, HB. Based on the observations of *Fig. 8.a.* and *Fig. 8.b.* it can be reasonable to choose the apparent peak hardness as the representative value of hardness corresponding to the compressive strength of concrete.

7. Conclusions

In the technical literature limited number of researchers investigated cement mortars and concretes by the Brinell method and most of the studies applied only one or two load levels trying to find a relationship between the Brinell hardness and the compressive strength of concrete.

Present paper summarizes the findings of static ball indentation studies on hardened concretes with water-cement ratios of 0.40, 0.50 and 0.65 tested at the age of 3, 7, 14, 28, 56, 90 and 240 days, at several load levels.

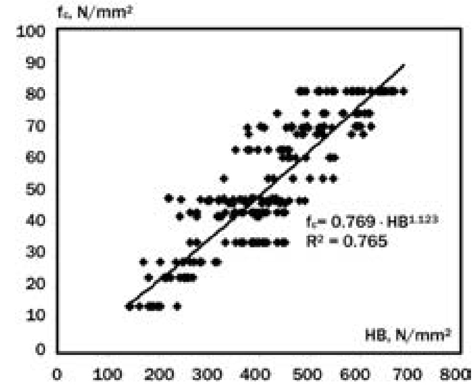

Fig. 7. The general linear relationship between compressive strength and Brinell hardness of concrete (results are separated neither by water-cement ratio nor testing load)
7. ábra A beton nyomószilárdsága és Brinell keménysége közötti általános lineáris kapcsolat (az eredményeket sem a v/c, sem a terhelési szint szerint nem különítettük el)

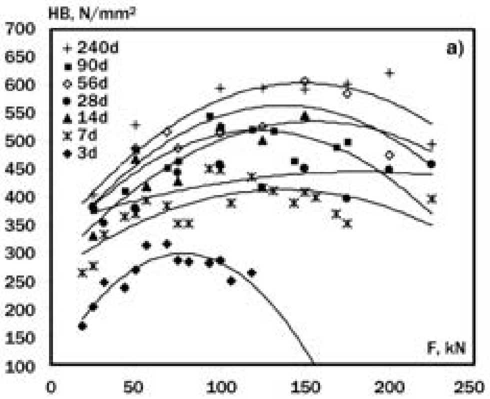

Fig. 8.a. *Brinell hardness (HB) results in time for specimens of w/c = 0.50 as a function of the testing load*

8.a. ábra *A v/c = 0,50 víz-cement tényezőjű próbatestek Brinell keménysége az idő és a teherszint függvényében*

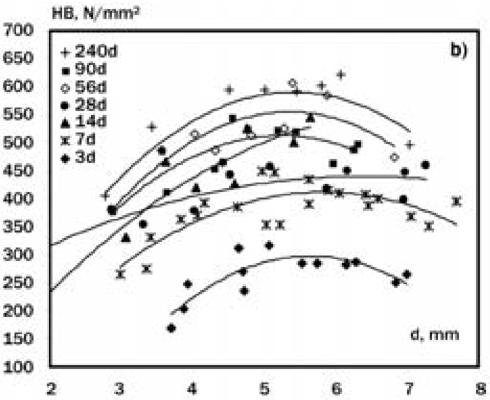

Fig. 8.b. *Brinell hardness (HB) results in time for specimens of w/c = 0.50 as a function of the residual indentation diameter*

8.b. ábra *A v/c = 0,50 víz-cement tényezőjű próbatestek Brinell keménysége az idő és a maradó golyónyom átmérőjének függvényében*

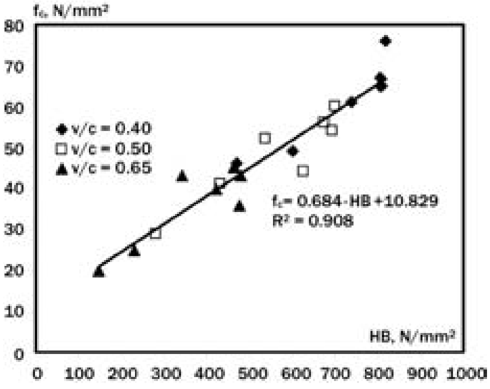

Fig. 9. *The linear relationship between the compressive strength and the peak Brinell hardness of concrete*

9. ábra *A beton nyomószilárdsága és a maximális Brinell keménysége közötti lineáris összefüggés*

The results demonstrated that the Meyer power functions can be formulated for concrete in a similar way to that of metals.

It was found that the power in the Meyer relationship is apparently constant for concrete, independently of the water-cement ratio and the age at testing, while the multiplier in the Meyer relationship is very sensitive to both influencing factors.

The results disproved the hypothesis of the power function relationship between the residual indentation diameter and the compressive strength of concrete with a power of -4.0 published earlier in the technical literature. The results confirmed the existence of a linear general model for the relationship between the compressive strength and the Brinell hardness, HB of concrete. During the experiments a special observation was made that clearly illustrates the elastic-plastic behaviour of concrete under the ball indenter as well as the mechanism of local densification and the formation of cone cracking. The results can add to the fundamental understanding of hardness of concrete and mark the direction of future research in the field.

8. Appendix – Hardness values

The Brinell hardness, HB can be calculated as the ratio of the indenter load and the surface area of the residual spherical imprint:

$$HB = \frac{2F}{D\pi\left(D - \sqrt{D^2 - d^2}\right)}$$

The Meyer hardness, HM can be calculated as the ratio of the indenter load and the projected area of the residual imprint:

$$HM = \frac{4F}{d^2\pi}$$

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Katalin **Szilágyi** – Adorján **Borosnyói** – Kristóf **Dobó**: *Static indentation hardness testing of concrete: a long established method revived.* Építőanyag, 63. évf. 1-2. szám (2011), 2–8. p.

Egy régi módszer új nézőpontból: megszilárdult beton statikus keménységmérése

A keménységvizsgálat lehetőséget nyújt arra, hogy az anyagok szilárdságról a közvetlen nyomószilárdság és húzószilárdság vizsgálatnál egyszerűbb módon jussunk információhoz. Mindazonáltal a keménység kontaktmechanikai megközelítésében és ezzel a keménység elméleti hátterében számos tisztázatlan terület van napjainkban is. A szakirodalomban csak korlátozott számban áll rendelkezésre cementhabarcs és beton statikus keménységvizsgálatával kapcsolatos kísérleti eredmény. A szakirodalomban azt találtuk, hogy a Brinell keménység és a nyomószilárdság kapcsolatának leírására alkalmas lehet egy hatványfüggvény abban az esetben, ha a vizsgálat során egyetlen teherszintet alkalmazunk. Viszont sokkal részletesebb elemzésre nyílik lehetőség, ha a vizsgálatot több teherszinten végezzük el. Ez esetben a terhelőerő és a maradó golyónyom átmérője közötti összefüggésekre beton szilárdsági osztályonként (ill. víz-cement tényezőnként) külön hatványfüggvényeket illeszthetünk, $F \propto a \times d^n$, amelyeknek paraméterei – Meyer (1908) kísérletei szerint – fémek esetében anyagjellemzőknek tekinthetők. Jelen kutatás célja normál testsűrűségű beton próbatestek statikus keménységvizsgálata több teherszinten, Brinell elven, golyóbenyomódással vizsgálva, a beton széles szilárdsági tartományában, számos vizsgálati korban. Kísérleti eredményeink alapján úgy találtuk, hogy a Meyer-féle hatványtörvény kitevője látszólag konstans, függetlenül a víz-cement tényezőtől és a beton korától, míg a szorzója mindkét befolyásoló tényezőre érzékeny. Az eredmények szerint a szakirodalomban publikált nyomószilárdság és maradó golyónyom kapcsolatát leíró hatványfüggvény -4-es kitevője nem valós feltételezés. Az eredmények megerősítik a nyomószilárdság és a Brinell keménység között feltételezhető általános lineáris összefüggést; az ezt leíró hatványfüggvény átlagos kitevője 1,128-ra adódott.

Kulcsszavak: beton, nyomószilárdság, Brinell keménység, Meyer keménység

FOLYÓIRATSZEMLE

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Kay Wille, Antoine E. Naaman, Gustavo J. Parra-Montesinos**:**
Ultra nagy teljesítőképességű betonok 150 MPa értéket meghaladó nyomószilárdsággal: Egy egyszerű módszer
(Ultra-High Performance Concrete wit Compressive Strength Exceeding 150 MPa (22 ksi): A Simpler Way)

A szerzők kiterjedt laboratóriumi kísérletsorozatot végeztek abból a célból, hogy ultra nagy teljesítőképességű beton (UHPC) készítésének olyan technológiáját dolgozzák ki, amelyben az építőipari piacon egyszerűen beszerezhető alapanyagok felhasználásával, speciális betonkeverő berendezések és hőérlelés nélkül lehet elérni legalább 150 MPa beton nyomószilárdságot.

Eredményeik alapján a következő megállapításokat és javaslatokat tették az UHPC beton összetételére vonatkozóan:

- A legkedvezőbb reológiai tulajdonságok és a legnagyobb nyomószilárdság kis C_3A (<8%) tartalmú portlandcementtel érhetők el.
- A homok 0,8 mm legnagyobb szemnagysága esetén az optimális homok-cement arány 1,4.
- A szilikafüst optimális közepes szemcsemérete 1,2 µm, 125000 cm^2/g fajlagos felülettel (szemben az irodalomban korábban publikált 0,5 µm alatti közepes szemcsemérettel). Ilyen szemcseméretű szilikafüst esetén az optimális adagolási mennyiség 25% a cement tömegére vonatkoztatva.
- Az optimális tulajdonságok elérése érdekében nagyobb közepes szemcseméretű (1,7 µm) szilikapor alkalmazása is szükséges, amelynek az optimális adagolási mennyisége szintén 25% a cement tömegére vonatkoztatva. Így a por alakú összetevők optimális keverési aránya 1:0,25:0,25 cement:szilikafüst: szilikapor.
- A víz-cement tényezőt (v/c = 0,16–0,27) és a folyósító adalékszer (polikarboxilát) mennyiségét (1,4–2,4%) az optimális konzisztenciához igazítva lehet fölvenni.

Eredményeik alapján a következő megállapításokat és javaslatokat tették az UHPC beton készítésre vonatkozóan:

- A szilikafüstöt és a homokot szárazon kell keverni öt percig.
- Ezt követően kell adagolni a többi por alakú összetevőt (cement, szilikapor) és újabb öt percig keverni.
- A vizet egy percen belül kell a keverőbe juttatni.
- Ezt követően a folyósító adalékszer teljes mennyiségét egyidejűleg a keverőbe kell adagolni, és a keverést további öt percig folytatni.

A szerzők célja az volt, hogy egyszerűsített módszerrel legalább 150 MPa nyomószilárdságú UHPC beton készítése váljon lehetségessé. Módszerükkel 115–206 MPa nyomószilárdság érhető el a keverék összetételétől függően.

Dr. Borosnyói Adorján