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New scientific results of the Ph.D. thesis

Mechanical testing and modelling of porous construction materials

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1. INTRODUCTION AND RESEARCH SIGNIFICANCE

Present PhD research provides laboratory tests and numerical analyses in which the mechanical testing of porous construction materials was carried out by various test methods to fill the gap in the literature in this topic. The expected results of the research program will contribute to a better understanding of the investigation and behaviour of porous construction materials and to the development of material models.

Non-destructive test methods (especially hardness testing) has a widespread and well-detailed literature in case of homogeneous materials, however in case of porous materials the literature is lacking of consistent results and conclusions. Besides that, the majority of the research in the topic are out of date, since then new approaches and devices were developed that could provide more insight to the behaviour of the material. Numerical models could be one of those approaches that are able to describe the inner micro or macro structure of a porous material. Using non-destructive test methods and numerical models it could be achieved that from a single piece of material a large number of data would be available leading to the decrease of the required (in some cases costly or not even possible) destructive laboratory tests.

One of the aspects of material testing that was well-studied but till now no conclusive proof was derived and no comprehensive model was described is the size effect on the compressive strength of concrete. According to Bažant the topic should be further studied using numerical methods, especially using Discrete Element Method (DEM), to understand the processes inside the material during its failure (Bažant, 1999). The most widely used engineering modelling approach, the Finite Element Method, is not well suited for discrete problems like this. However, the DEM is nowadays on a research level phase and not easily usable for the engineering practice mostly due to the long-lasting calibration process of a model. Thus it would be practically useful to create methods that can decrease this calibration phase to make DE models faster to use for engineers. It gives a significance to this PhD thesis that numerical models are supported by laboratory tests, analytical and microstructural analyses of the materials are included.

Our world moves to a direction where apart from the strength and durability of a structure, its sustainability becomes more and more important. Therefore, advanced types of concretes shall be developed that possess high strength, good durability and are sustainable. A promising way to develop this new green version of concrete is replacing a specific amount of its ingredients by recycled materials, such as construction wastes that cannot be reused other ways, but available in large amount. Large amount of construction waste is produced in a powder form by the construction industry. Some of these materials can be advantageous for the properties of concrete thus it is worth to investigate them in more depth: by doing so not only some waste material is eliminated but the properties of concrete can be improved too.

2. SCOPE AND LIMITATIONS

In the present research the mechanical testing and the modelling of porous construction materials is studied. The PhD thesis has two major sections:

1. In the first section a wide range of structural construction materials is investigated through laboratory tests (compressive strength test, different versions of hardness tests, Young's modulus test, density) and numerical

modelling methods (Discrete Element Method). The tested materials were the following:

- Concretes: normal strength concrete, high-strength concrete, concrete containing supplementary cementitious material (SCM; e.g. metakaolin (MK)), polymer concrete.
- Other calcium silicate hydrate (CSH) based materials: cellular concrete block (Ytong), sand-lime brick (Silka).
- Ceramics: clinker brick, facebrick, clinker tile.
- Natural stones: porous limestone and compact limestone, rhyolite tuff.
- Metals: aluminium, mild steel, reinforcing steel.

2. In the second section the focus was on concrete, the most widespread porous construction material. The mechanical properties of different concretes were evaluated. This section has three major sub-sections focusing on properties of concrete that has significant effect on the mechanical performance.

a) To study the effect of aggregate type, the main variables of the concrete mixes were the following (*Table 1*):
   - the type of aggregate: natural gravel, crushed stone, lightweight aggregate; on normal strength concrete;
   - the particle size distribution of the aggregates: A and C grading curves and no-fines as well; on normal strength concrete;

Table 1 *Variable and constraint parameters for all mixtures used for the aggregate type studies*

Variables
1. *Aggregate type: quartz gravel; crushed stone; lightweight (Liapor)*
2. *Aggregate particle size distribution (%)*
2.1 0/0.5 0 – to - 40
2.2 0.5/4: 0 – to - 30
2.3 4/8: 15 – to - 100
2.4 8/16: 0 – to - 50
Constraints
3. *d_{max} (mm): 16*
4. *Cement type: OPC - CEM I 42.5 N*
5. *w/c ration (by mass): 0.67*
6. *Cement content (kg/m^3): 264*

From these mixes 150 mm cubes were prepared for compressive strength tests.

b) The effect of a waste material (cellular concrete powder - CCP) in the form of fine powder was investigated and compared to other waste materials and to traditional SCMs, like metakaolin:
   - in cement mortar (CEM I 42.5 N cement; w/c = 0.5)
   - in case of normal strength concrete (C20/25)
     - CEM I 42.5 N cement (270 kg/m^3); w/c = 0.57; d_{max} = 16 mm
   - in case of high strength concrete (C60/75).
     - CEM I 42.5 N cement (325 kg/m^3); w/c = 0.40; d_{max} = 16 mm

The applied CCP had the maximum particle size (d_{max}) less than 0.09 mm. The findings of this section are only valid in case of CCP with particle size less than 0.09 mm. The applied amount of cement supplementary materials (in percentage of the cement amount) were the following:

- CCP: 0 to 17%
- MK: 10%
- CCP-MK mix: 3 and 7%
- Clay brick powder: 10%

From every mix 150 mm cubes were prepared for compressive strength tests, 100 mm edge length cubes for freeze-thaw resistance tests. From the cement pastes 40×40×160 mm prisms were prepared for flexural-tensile strength test and compressive strength test.

c) In case of the investigation of size effect the focus was on normal strength concrete, which is in this thesis corresponds to concretes with strength classes between C20/25 and C50/60. The findings of this section are limited to that range of compressive strength. The variables and constraints corresponding to mixtures of all produced concretes are shown in *Table 2*. The main variable parameters were the cement content, aggregate particle size distribution and water-to-cement ratio, while the other parameters were kept constant. Finally, five mixes of different strength classes were produced that were casted into different size cube and cylinder moulds producing around 150 specimens that were subjected to compressive strength test.

Table 2 *Variable and constraint parameters for all mixtures used for the size effect studies*

	Variables
1.	*Cement content (kg/m³): 264 – to – 500*
2.	*w/c ratio (by mass): 0.35 – to - 0.67*
3.	*Aggregate particle size distribution (kg/m³)*
	3.1 0/4: 594 – to - 910
	3.2 4/8: 357 – to - 542
	3.3 8/16: 447 – to - 733
	Constraints
4.	*d_{max} (mm): 16*
5.	*Cement type: OPC - CEM I 42.5 N*
6.	*Aggregate type: quartz gravel*

The findings related to the numerical simulations are only valid in case of applying Discrete Element Method, where the particles are modelled as rigid spheres (or as their bulks) and the material model is described in the contacts between the elements.

In general in the applied concrete mixtures the amount of components were within their normal range and the applied component variants were the most generally applied in the construction industry (except where it is specified otherwise) considering that they would not have special effect on the investigated property (e.g. that is why CEM I cement was applied):

- particle size distribution within A and C grading curves (*EN 12620*),
- CEM I 42.5 type OPC (*EN 197-1*),
- aggregate was natural gravel (except in the study where the effect of aggregate type was investigated),
- water-to-cement ratio was between 0.35 and 0.67,
- where it was needed SIKA Viscocrete 5 Neu type of plasticizer was applied in the minimum possible amount.

In sum approximately 800 samples were prepared and investigated. More than 300 studies in research papers, theses, books and standards were reviewed, and excerpts from them were used in the preparation of this thesis, which may serve as a valuable document for researchers working in this field.

3. AIMS AND OBJECTIVES

An aim of this research was to investigate testing methods (either laboratory tests or modelling approaches) that reduce the number of required destructive material tests. It is beneficial in case of the inspection of already existing buildings and structures (including heritage buildings), where only a limited number of test samples can be acquired. Renovation of building is an environmentally favourable approach (instead of demolishing and rebuilding), however the extension of lifespan of a load bearing structure is only allowable if it was proven that it has sufficient load bearing capacity. The most widespread test method for the non-destructive testing of structural materials is hardness test. In case of porous construction materials hardness test was only applied in a form of dynamic hardness tests, which accuracy falls below the accuracy of destructive laboratory tests. Static hardness test are more advantageous in this aspect, however they were rarely applied for porous materials in the past. This PhD thesis is aiming to reach a better understanding on the processes in the material during a hardness test. Further aim of this thesis is to provide a deeper analysis about the open topics of mechanical testing and modelling of porous materials in focus to the most widely used porous construction material, concrete.

To reach these aims the following objectives were defined for this PhD thesis:

- Find a hardness testing method that is able to provide appropriate amount of information on the behaviour of porous construction materials.
- Define a modelling approach that is suitable for the modelling of concrete and investigate the possibilities of the modelling of material testing in numerical environment:
    - the model shall be able to follow the different particle size distributions,
    - the model shall be able to follow the response of the material similarly (with an acceptable accuracy) to different types of loading schemes after a proper calibration.
- Investigate the effect of the major influencing factors (like size of the specimens, aggregate type and distribution, effect of recycled materials) on the laboratory test and the numerical modelling of concrete.
    - Find a recycled material which potentially can be used in a concrete mix
        - Investigate the effect of the material on the mechanical and durability properties of concrete.
        - Analyse the inner structure of the material.
    - Define an approach how the different type of aggregates (crushed stone, lightweight aggregate) can be considered in a numerical model.
    - Investigate how specimen size effect the compressive strength of concrete and how it influences the numerical model parameters.

4. EXPERIMENTAL PROGRAM

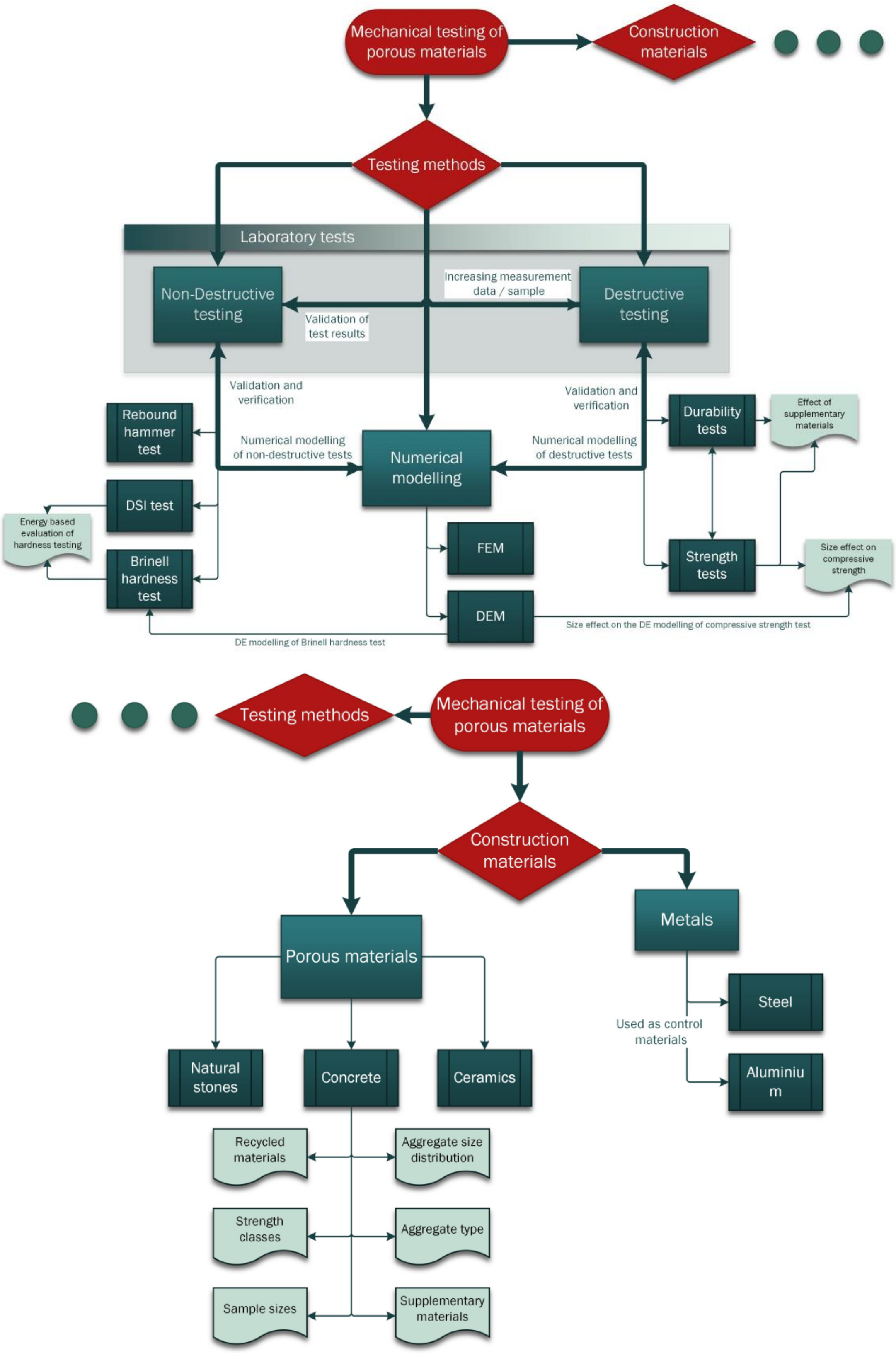

***Fig. 1** Overall research program*

The research program of this PhD thesis can be divided into two main parts. In the first part porous materials in general were investigated using various types of mechanical testing methods. In the second part the focus was on the most widely used porous construction material, concrete. Based on literature three major topics were chosen within the material testing of concrete that are insufficiently studied in the literature: numerical modelling of concrete (and numerical modelling of material tests), size effect on the compressive strength of concrete, the effect of recycled materials on the strength and durability of concrete (*Fig. 1*).

The research program incorporated the following major parts:

1. Mechanical testing of porous construction materials
    a. Mechanical testing methods were studied from the literature and DSI was selected as a potential method for hardness testing of porous materials.
    b. A wide range of construction materials were selected (see them in *Chapter 2*). The selected materials were subjected to compressive strength test, Brinell-hardness tests, DSI test, Rebound hammer test, Young's modulus test, density measurement. The results were analysed, the relationships of the properties were investigated on energy basis as well.
    c. Numerical methods for modelling porous materials were studied and DEM was chosen as a potentially favourable option.
2. Mechanical testing and modelling of concrete
    a. DE model of concrete as well as for compressive strength and hardness tests was created. An estimation model was developed to estimate the normal strength of parallel bonds in the DE model, which is the major influencing factor of compressive strength of a DE model.
    b. Besides the effects of its components the compressive strength of concrete is dependent on the specimen size as well. Contradicting results can be found in the literature on this topic. For the investigation of the topic normal strength concrete specimens of various sizes and strength classes were tested.
    c. After that it was investigated how the size effect can be considered in a numerical model and how well the numerical model represents this phenomena.
    d. The effects of different particle size distribution and aggregate type were studied using the above described model. For that compressive strength tests in laboratory were performed on different concretes (see *Chapter 2*). Among the chosen aggregates there were some recycled materials as well. The materials were subjected to hardness test as well.
    e. Recycled materials can be applied in concrete mixes in powder form as well, which is less covered in the literature than their application as coarse aggregate. The fine powders in the concrete cannot be modelled in DE, only can be taken into account in the strength parameters. However, in real life they can have significant effect on the mechanical and durability properties of concrete. Thus the effect of recycled materials in powder form on the mechanical and durability properties of concrete were studied, using a waste material powder (CCP), which is easily available in large amount, but was not studied before in this form. CCP were tested for strength and durability and its microstructure were analysed to understand its influence on concrete. The samples were subjected to compressive strength test and hardness tests, as well they have been modelled in DEM.

5. NEW SCIENTIFIC RESULTS

This chapter represents the main new scientific results, which have been proven through this work based on the conducted experimental program and analytical studies.

1. New scientific results about hardness of porous construction materials

Where;

- *F: loading force during hardness test [N];*
- *d: indentation diameter measured during hardness test [mm];*
- *DEM: Discrete Element Method;*
- *HB: Brinell-hardness;*
- *W_t: total indentation work related to hardness test;*
- *W_e: elastic indentation work related to hardness test*

Porous stone-like construction materials and metals have been studied for surface hardness, applying static indentation hardness methods (Brinell and DSI). The materials tested were the followings: aluminium, mild steel, reinforcing steel, two types of coarse limestone, compact limestone, rhyolite tuff, normal strength concrete, high strength concrete, polymer concrete, clinker tile, clinker brick, facebrick, sand-lime brick, cellular concrete. In addition to non-destructive tests, destructive tests were performed on each material to determine their mechanical properties (compressive strength, modulus of elasticity, density). The test methods (compressive strength and hardness) were modelled using Discrete Elemental Method. My research demonstrates the following new scientific results:

1.1 I have confirmed through laboratory experiments on porous construction materials that the relationship between the loading force and the square of the residual indentation diameter is linear during ball indentation tests. Consequently, the exponent *n* in Meyer's power law is exactly 2 for porous construction materials. The multiplication factor *a* in Meyer's power law is material-dependent, and can be determined individually for each porous construction material [1][2] **and** *Fig. 2*. **I have confirmed that a peak value is observable in the Brinell-hardness when represented as a function of the loading force** [1][2] **and** *Fig. 3*. **My observations confirm and extend the validity of a hypothesis given about this peak for concretes, to other porous construction materials.**

<u>Scientific background:</u>

Brinell-hardness depends on the loading force under which the test is conducted. The relationship between the loading force and the indentation size – in case of spherical indenter – can be described with empirical equations. According to Meyer, using the same indenter at different load levels the value of hardness is different (Meyer, 1908). It can be described with a power law (named after Meyer):

$$F = a \times d^n \tag{1}$$

Eq. (1) describes the relationship between the loading force and the indentation diameter. The parameters *a* and *n* are material characteristics. Based on the available literature data the value of *n* is higher than 2, in most cases it falls between 2 and 2.5. In the literature it is also described that the value of *n* in case of raw materials is around 2.5, while in case of processed materials it is around 2. I have investigated the relationships between the loading force and the indentation depth as well as the indentation diameter. My observations confirmed the existence of a linear relationship between the loading force and the indentation depth. Using the geometrical equation that describes the relationship between the indentation depth and diameter, it can be proven that the value of the exponent n in Meyer's power law is exactly 2 in case of porous construction materials, as it can be seen in *Fig. 2*. The multiplication factor a in Meyer's power law is material-dependent and can be determined individually for each material [1][2].

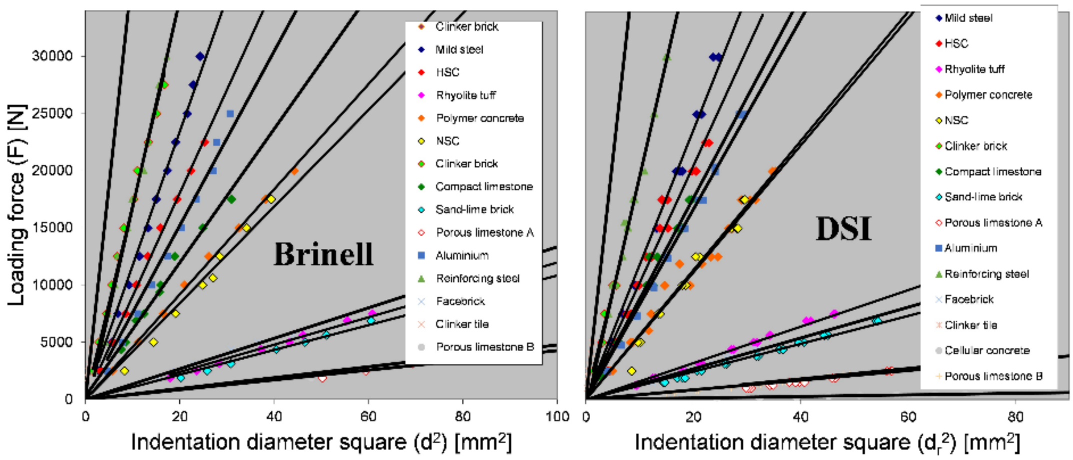

Fig. 2 *The loading force in function of indentation diameter square (in case of DSI the residual indentation diameter square) in case of Brinell test (left) and DSI test (right) for the materials tested*

It was published in the technical literature for concretes that a maximum value can be observed in the Brinell-hardness plotted as a function of the load (Szilágyi et al, 2011). My experimental results confirmed this specific behaviour for other porous construction materials too: the existence of a maximum value in the Brinell-hardness plotted as a function of the loading force was observed. *Fig. 3* shows the calculated Brinell-hardness results represented as a function of the testing load during hardness tests. The apparent peak hardness values are visible in each case [1][2].

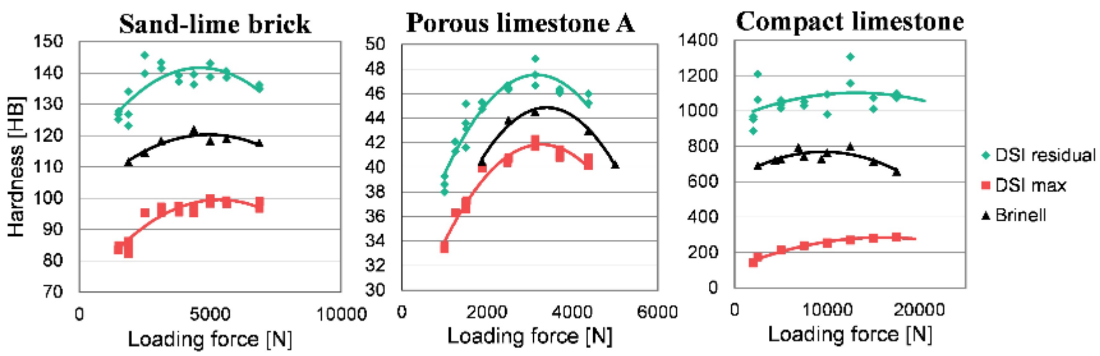

Fig. 3 *Brinell-hardness in function of the loading force for other porous materials*

1.2 I have confirmed through laboratory experiments on porous construction materials that the DSI method is applicable, and provides a robust tool to increase the precision of deformation readings (both for maximum and residual indentation diameters) and makes the indentation energy based hardness analysis possible. I have confirmed that the indentation energy has much closer connection to the mechanical parameters (Young's modulus, compressive strength) than the indentation diameter based on Brinell tests. I have defined a linear relationship between the peak Brinell-hardness and the ratio of the total and elastic indentation energy, and I confirmed its validity for plastic and elasto-plastic porous construction materials [1][2][6][7]**.**

Scientific background:

I confirmed through extensive laboratory experiments that Depth Sensing Indentation (DSI) method is also applicable for hardness testing of porous materials, and in terms of accuracy and data processing it is even more advantageous:

- No measurement error from the reading of the indentation diameter (instead of ±0.1 mm the accuracy of the measurement is ±2 μm),
- DSI test gives data about the maximum and the residual indentation diameter as well, besides the full loading-unloading curves of the test. Using these data the hardness testing can be analysed based on the indentation energy. Indentation energy has much closer connection to the mechanical parameters (Young's modulus, compressive strength) than the indentation diameter that is available from a traditional Brinell-hardness test [1][2][6][7].

Loading-unloading curves of DSI test (*Fig. 4*) can help to classify the materials into three groups (elastic, elasto-plastic and plastic) based on their mechanical behaviour. The classification can be made based on the shape of the loading-unloading curves and the slope of the loading and unloading paths. If the slope of the unloading path is close to a vertical line (ratio of the residual to maximum displacement is higher than 85%) then the material can be considered as plastic, while if the loading and unloading paths are close to each other (ratio of the residual to maximum displacement is lower than 15%) then the material can be considered as elastic. Between these two boundaries the materials can be considered as elasto-plastic [2][16]. In *Fig. 4* some typical results of the DSI tests can be seen. Based on these figures the tested materials are:

- elastic materials (clinker tile, clinker brick),
- elasto-plastic materials (compact limestone, rhyolite tuff, normal strength concrete, high-strength concrete, polymer concrete, facebrick)
- plastic materials (sand-lime brick, cellular concrete, porous limestone).

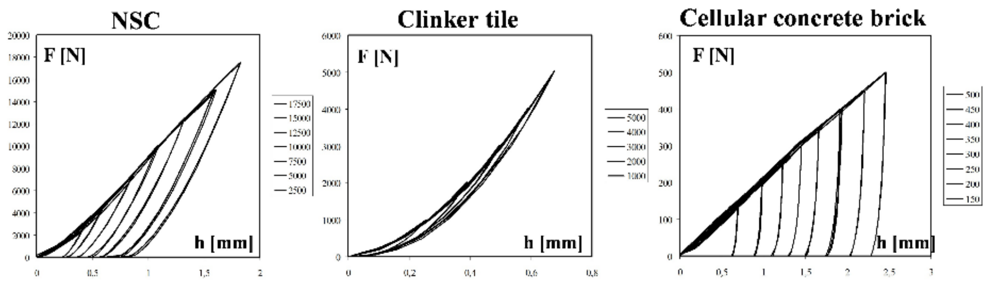

***Fig. 4** DSI test results: (a) normal strength concrete – elasto-plastic, (b) clinker tile – elastic and (c) cellular concrete brick - plastic*

Based on the loading-unloading curves the behaviour of a material can be analysed on the energy level. The energy-based analysis of the DSI results indicated that there is a linear relationship between the Brinell-hardness and the elastic indentation energy of elasto-plastic and plastic construction materials (compact limestone, high-strength concrete, polymer concrete, normal strength concrete, rhyolite tuff, facebrick, aluminium, mild steel, reinforcing steel, sand-lime brick, porous limestone, cellular concrete), *Fig. 5*. The peak Brinell-hardness (*HB*) is represented as a function of the ratio of the total (W_t) and the elastic (W_e) indentation energy (*Eq. (2)*) with a strong correlation. *Eq. (1)* is applicable for all investigated materials, except the elastic materials (like clinker tile) [1][16].

$$HB = k \cdot \frac{1}{\left(\frac{W_t}{W_e}\right)^2} \tag{2}$$

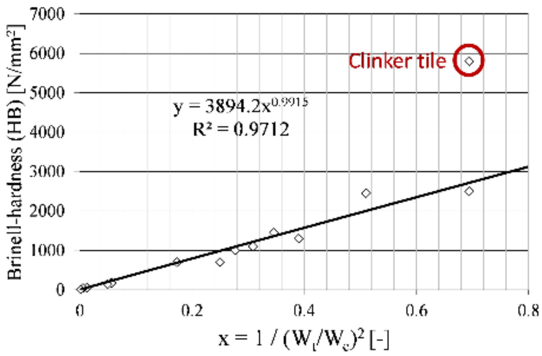

Fig. 5 *Relationship of the Brinell-hardness and the ratio of the total and elastic energy*

1.3 I have confirmed through numerical experiments on concretes that Discrete Element (DE) models can be constructed to describe both the linear relationship between the square of indentation diameter and loading force during ball indentation tests, (*Fig. 6*)**, and the peak value of Brinell-hardness represented as a function of the loading force,** (*Fig. 7*) [3][5][6][7][9]**.**

Scientific background:

The behaviour described in Thesis 1.1 can be modelled by DEM, calibrated with the compressive strength. I have developed a DE model based on the following main inputs: density, aggregate size distribution, compressive strength. The model is capable of simulating the elastic-plastic behaviour of concrete. Using this model the special characteristics of hardness can be observed on the DE model results:

- The relationship between the square of indentation diameter and the loading force is linear (*Fig. 6*).
- There is a maximum value of Brinell-hardness when plotted as a function of the loading force (*Fig. 7*), which was detailed in Thesis 1.1.

The figures show that the correlation coefficient of the results is high. [3][5][6][7][9].

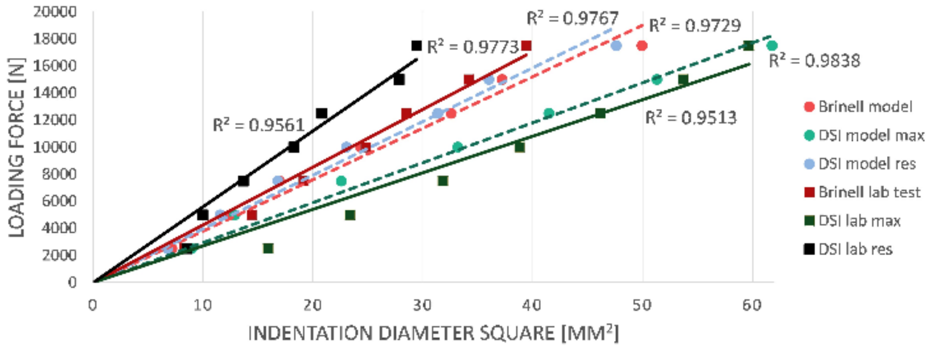

Fig. 6 *Indentation diameter square vs loading force in case of all DE model and lab test results*

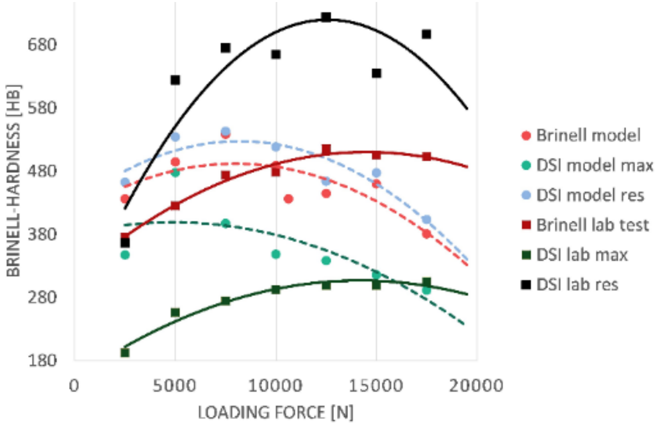

Fig. 7 *Brinell-hardness in function of the loading force for the models and their corresponding lab test*

2. New scientific results about size effect on compressive strength of concrete

Where; *Mix 1 is a C20/25, Mix 2 is a C30/37, Mix 3 is a C35/45, Mix 4 is a C45/55 and Mix 5 is a C50/60 strength class normal concrete.*

- *B, S and α are empirical constants of the MSEL (Modified Size Effect Law);*
- *d is a length dimension of a specimen;*
- *A is the cross-sectional area of a specimen;*
- *V is the volume of a specimen.*

The compressive strength of concrete strongly depends on the specimen size. In case of the laboratory testing and modelling of concrete it would be advantageous to apply smaller size specimens; however, for that the size effect should be investigated in more depth. My research demonstrates the following new scientific results:

2.1 I have developed a new algorithm that can provide the compressive strength of normal strength concretes (C20/25-C50/60) in the range of 2200-2400 kg/m^3 body density for standard test specimens (150 mm cube or ∅150/300 mm cylinder) with acceptable accuracy. [20]

<u>Scientific background:</u>

The estimation model is based on the generalized version of Modified Size Effect Law (MSEL), which approximates the nominal strength of concrete members based on their size, direct tensile strength, maximum aggregate size and empirical parameters. My model shows higher accuracy in case of cube specimens and similar accuracy in case of cylinder specimens compared to the estimation models available in the literature (Kim, 1999; Del Viso, 2002).

The algorithm for model training is structured as follows (*Fig. 8*):

1. Based on a relatively small set of laboratory measurement data (compressive strength test results on cubes and cylinders of various sizes (50-200 mm edge length cubes; 60-150 mm diameter cylinders) made of normal strength concretes (C20/25-C50/60) with different strength classes) a model equation is defined in the form of power law.
2. Using the curves acquired from the model equation new data points are defined. This step is useful for the optimization algorithms, thus they are able to find a more realistic parameter set.
3. Multi-parameter optimization is performed on the parameters (*B, S* and *α*) of the estimation model, taken into account the shape (cube or cylinder) and the known dimensions (*d, A* or *V*) of the specimen. As a results 2 (shape) × 3 (dimension) = 6 parameter sets are determined.

As the model is trained and the parameter sets are available, based on the standard compressive strength of a concrete specimen, the compressive strength of any size specimen can be determined, or vice versa. This estimation step utilizes the observation the within the range of normal strength concretes the relationship of the compressive strength of the standard cylinder and cube can be described with linear regression.

The model can be used for the normal strength of parallel bonds of a DE model as well. Using the above algorithm supplemented with this step, based on the standard compressive strength of a given concrete the parallel bond strength of any size of specimen can be determined with acceptable accuracy. [20]

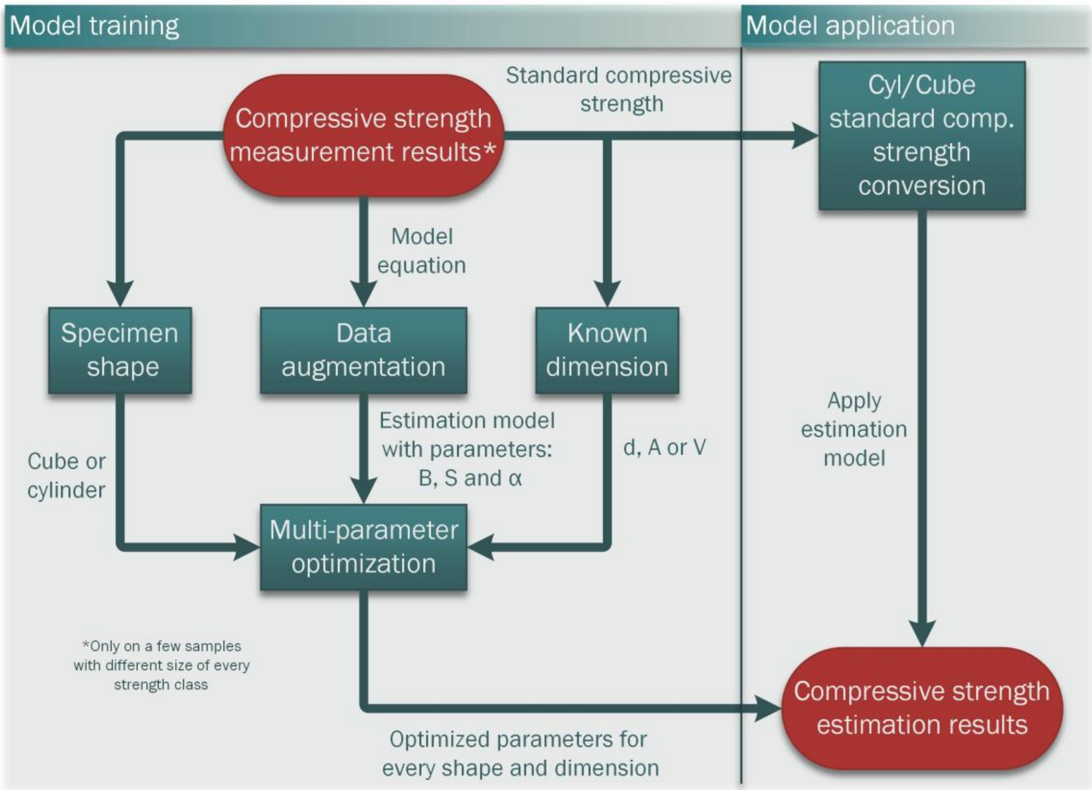

Fig. 8 *Flow chart of the algorithm developed for the consideration of size effect*

2.2 I have confirmed through laboratory experiments with normal strength concretes on a wide range of geometry of cylinder and cube specimens that the size effect (defined as the specimen compressive strength related to the strength of the standard size specimen) is higher for concretes of lower strength and lower for concretes of higher strength. The strength ratio shows a linear relationship over the studied range of strength (C20/25-C50/60) [20] and *Fig. 9*. **I have also confirmed experimentally that the size effect is more significant on cube specimens than on cylinder specimens in the studied range of strength (C20/25-C50/60)** [20] and *Fig. 10*, *11* and *12*.

Scientific background:

My laboratory measurements revealed that the change of the strength ratio proportional to the strength of the standard specimen is higher in the case of concretes of lower strength. The relationship is linear for normal strength concretes (C20/25-C50/60), *Fig. 9*. A possible explanation van be that concretes with higher strength are usually less inhomogeneous than those with lower strengths [20].

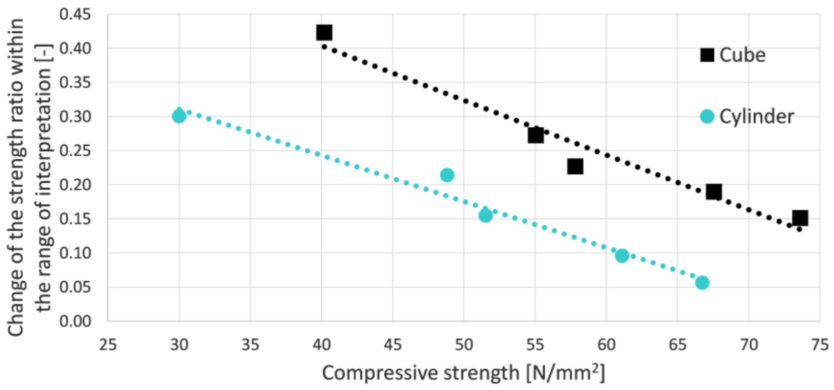

Fig. 9 *Change of the strength ratio within the range of interpretation of the 5 mixes in function of their standard compressive strength*

By looking at the curves and values in *Figs. 10* and *11*, it can be observed that the size effect is more significant in case of lower strength classes. The maximum and minimum values in case of Mix 1 (which has the lowest strength class: C20/25) are 1.32/1.29 and 0.90/0.99 for cubes/cylinders respectively, while in case of Mix 5 (which has the highest strength class: C50/60) these values are 1.13/1.05 and 0.95/0.99. The deviation of the values in case of the higher strength class is significantly lower, as it is shown in *Fig. 9*. This means that the size effect depends on the strength of the concrete specimen. In case of a lower strength concrete, the difference in compressive strength and Young's modulus between the cement matrix and the aggregate is significant, while in case of higher strength, the difference is decreasing. It is also worth mentioning that a lower strength concrete can be produced by many different mixes (different w/c, a/c, compacting, etc.), while in case of a high strength concrete, there are not that many variations.

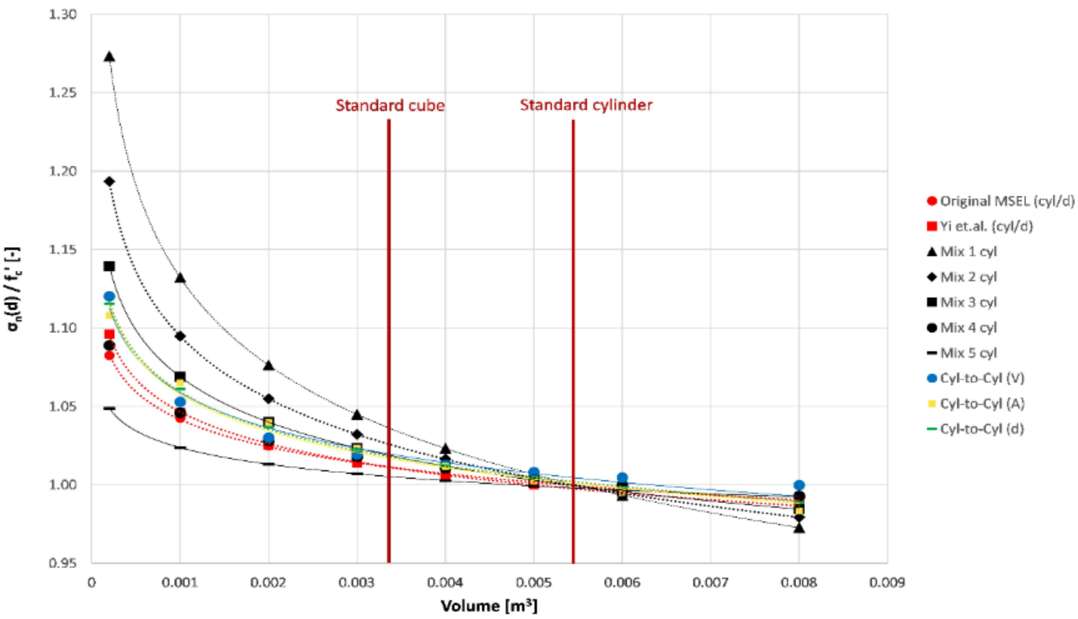

Fig. 10 *Results for estimating cylinder strength (red – literature; black -measurements; other – own estimation models)*

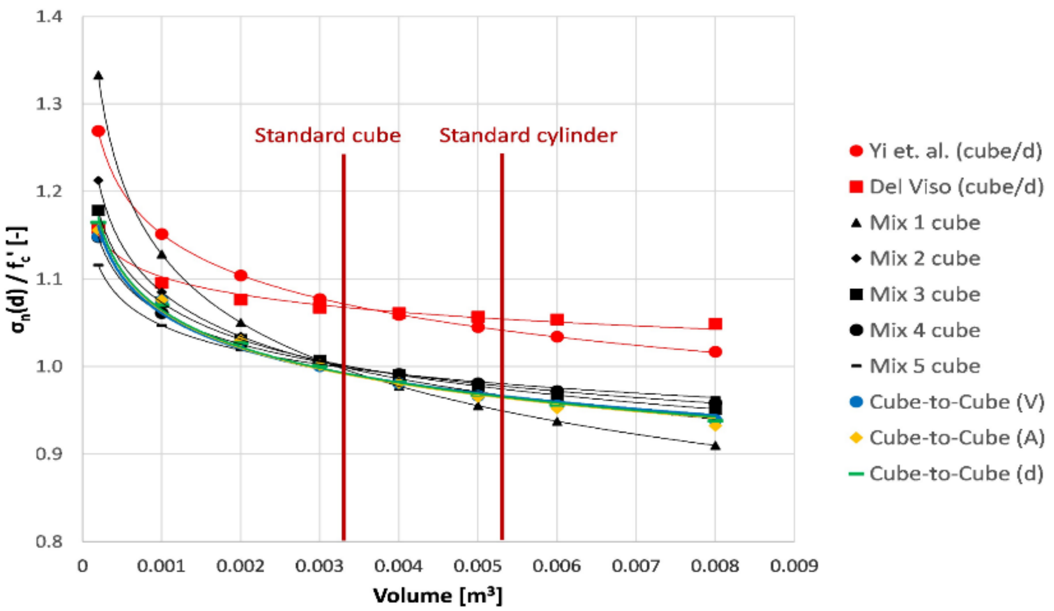

Fig. 11 *Results for estimating cube strength (red – literature; black – measurements; other – own estimation models)*

The laboratory experiments also confirmed that the size effect is more significant on the cube specimens (higher deviation in strength ratio), than on the cylinder specimens in case of normal strength concrete [20] and *Fig. 10*, *11* and *12*. This can be caused by the side ratios of the specimens and the size of the purely compressed zone. The strength ratios for cubes also have higher variation than the strength ratios for cylinders. In case of a 1:2 ratio cylinder during compressive strength test, the middle 1:1 ratio zone is not affected by the boundary conditions; in this zone, the failure of the specimen is caused by the tensile strength developed due to the Poisson effect, while in case of a cube, there is no such zone. Therefore, only a fraction of the whole volume of the cube specimen is taking part in the load-bearing, thus all small failures have higher effect on the compressive strength.

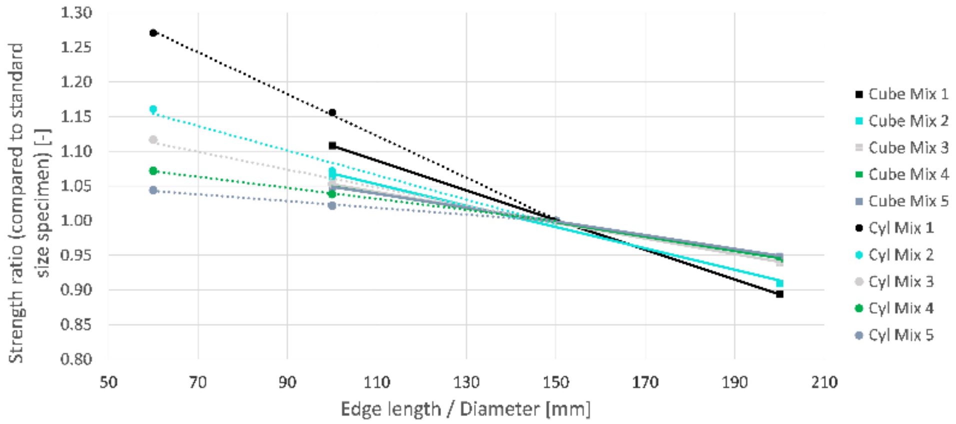

Fig. 12 *Strength ratio (compared to standard size specimens) vs Edge length / Diameter for all mixes (cube and cylinder results separately)*

2.3 I have confirmed through laboratory experiments that a limiting specimen volume can be found for both cube (0.006 m^3) and cylinder (0.004 m^3) specimens, above which the size effect on compressive strength can be neglected (i.e. less than 1% related to the standard compressive strength) [20]. **I have confirmed through numerical experiments and defined the value of the smallest specimen size for which a DE model can be considered as sufficiently accurate for parameter tuning and material generation of DE models as well as to predict specimen size effect.**

Scientific background:

The strength ratio decreases and approaches to a limit. This limit corresponds to a certain size for cubes and cylinders as well. This phenomenon was analysed by taking the difference between two strength ratio values that follow each other with 0.001 m^3. As an example, one of the mixes is shown here with numerical values in *Table 3*. The differences are always continuously decreasing, which shows (from an engineering point of view) that the functions are approaching to a limit (asymptotic). The limit value is the first volume, where the difference is smaller than a given threshold value, which, is 0.01 (1 %). For cubes it is 0.006 m^3 (~182 mm edge length cube), above which, regardless of the increase of the size, the compressive strength of the specimen will not decrease. 182 mm edge length is higher than the standard size (150 mm) but smaller than the maximum sample size used in this study (200 mm). For cylinders, this value is lower, around 0.004 m^3 (137 mm diameter 2:1 ratio cylinder). This value is smaller than the standard cylinder size, thus the standard size is appropriate for material testing. These values (182 mm for cubes and 137 mm for cylinders) are the minimum recommended sizes for compressive strength testing to cancel out size effect.

***Table 3** Compressive strength ratios and their differences*

Volume [m^3]	Mix 3			
	σ_c(d)/f_c' [-]		Difference [-]	
	Cube	Cylinder	Cube	Cylinder
0.0002	1.15	1.14	0.095	0.070
0.001	1.06	1.07	0.039	0.029
0.002	1.02	1.04	0.022	0.017
0.003	1.00	1.02	0.015	0.012
0.004	0.98	1.01	0.012	**0.009**
0.005	0.97	1.00	**0.009**	0.007
0.006	0.96	1.00	0.007	0.006
0.008	0.94	0.98	-	-

In case of DE models, it was found that using a 120 mm cube or 100 mm cylinder the compressive or parallel bond strength of a 200 mm edge length cube or 170 mm diameter cylinder can be estimated with acceptable precision. This leads to a significant reduction in computation time. The computation time of the material generation strongly corresponds to the number of elements (and contacts) and it shows a quadratic polynomial relation between them. Similarly to the element number, the computation time is also increasing according to a quadratic polynomial with the volume of the specimen. As it can be seen in *Fig. 13* in case of the larger samples the number of particles is high, which requires high computation effort (~30 hours), which is unacceptable for practical engineering application. In my research, I aimed to propose an approach which can decrease the required time necessary for material generation. As an example the substitution of a 200 mm edge length cube (400000 elements) with a 120 mm edge length cube (100000 elements) the runtime decreases to its third.

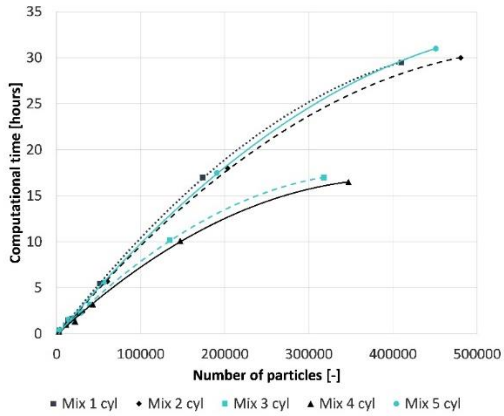

Fig. 13 *Computational time vs. Number of particles for all five mixes measured on cylinders*

3. New scientific results about the consideration of the aggregate type and size distribution in the modelling of compressive strength test of concrete using DEM

Where;

- f_{pb} *– normal parallel bond strength;*
- f_c *– compressive strength of the standard size cylinder/cube;*
- ρ *– body density of the specimen;*
- m_R *– multiplier factor, which describes the relationship of the compressive and the bond strength;*
- m_C *– multiplier that takes into account the effect of crushed aggregate;*
- m_L *– multiplying factor, taking into consideration the effect of lightweight aggregate;*
- m_N *– multiplying factor, which takes into account that only coarse aggregate is present in the aggregate frame;*
- m_{Dens} *– multiplying factor, which considers the effect of varying density in different mixes;*
- c_L*,* c_N *and* c_{Dens} *are empirical constants.*

The calibration of DE models is a time-consuming process. This is one of the main reasons, while DE software are not that broadly used in engineering practice. In a practical point of view it would be advantageous to define methods that supports the calibration process of a DE model.

My research demonstrates the following new scientific results:

3.1 I have confirmed through numerical experiments on normal strength concretes (C20/25-C50/60) in the range of 2200-2400 kg/m^3 body density that a linear relationship exists between the normal strength of parallel bonds in a DE model and the measured mean compressive strength of standard specimens (150 mm cube or ∅150/300 mm cylinder) [20]**.**

<u>Scientific background:</u>

The equation is valid for normal strength concretes with density between 2200-2400 kg/m^3. In most practical cases the parallel bond strength of a standard size specimen is not known, but rather the compressive strength of the standard size cylinder/cube. So the relationship of the parallel bond strength and compressive strength of standard size specimens was investigated. It was found that the same linear relation can be written for both cylinder and cube specimens, as it can be seen in *Eq. (3)* and *Fig. 14*.

$$f_{pb} = 0.79 f_c \tag{3}$$

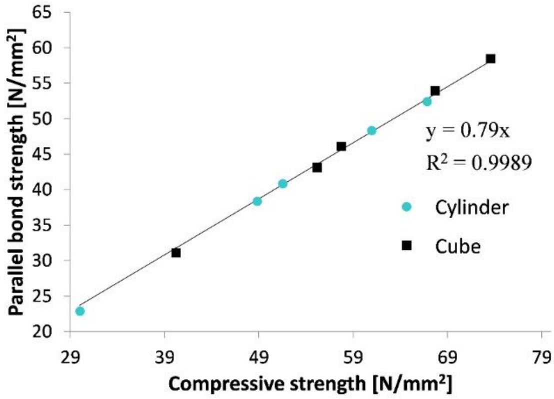

Fig. 14 *Parallel bond strength vs. Compressive strength for standard size specimens*

3.2 I have developed a new parameter optimization based estimation algorithm for the normal strength of parallel bonds in a DE model based on the measured compressive strength of concrete. The algorithm takes into account the effect of different aggregate types and particle size distributions [13] [17]**.**

Based on my laboratory measurements the estimation model approximates the final value with acceptable accuracy. The formulation of the problem is written in the following generalized formula:

$$f_{pb} = f(\rho, f_c) \tag{4}$$

where f_{pb} is the normal strength of the parallel bonds (DE model parameter), ρ is the density of hardened concrete and f_c is the compressive strength measured on real samples. Parallel bond strength and the density set in the model are the main influencing factors for the compressive strength measured in a DE model. If the particle size distribution of the model is given, then the normal strength of the parallel bonds (in case of a normal concrete) can be estimated as the function of the density and a multiplier factor, which describes the ratio of f_{pb} and f_c. In the current case, it is aimed to consider in this model the effect of the type of aggregate and the particle size distribution as well. All of these can be considered as multiplication factors. Lightweight aggregate and the particle size distribution (no-fines) are strongly connected to the density of the sample, thus these factors shall be given as the function of density.

The proposed generalized equation can be expressed in the following way:

$$f_{pb} = m_R \cdot m_C \cdot m_L(\rho) \cdot m_N(\rho) \cdot m_{Dens}(\rho) \cdot f_c \tag{5}$$

The optimized parameter set can be seen in *Table 4*. Using these parameters the model was tested on a larger data set, containing various types of concrete samples. The error (difference between the estimated and the calibrated parallel bond strength) of each test sample can be seen in *Fig. 15* plotted as a cumulative distribution function.

Table 4 *The optimized model parameters*

m_R [-]	m_C [-]	c_N [kg/m^3]	c_L [kg/m^3]	c_{Dens} [kg/m^3]
0.845	1.04	2022.9	2438.1	2153.9

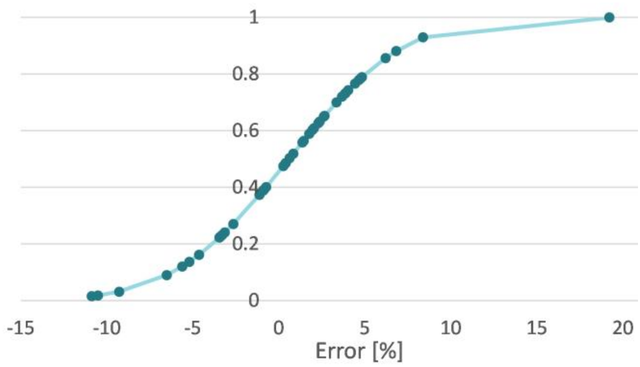

Fig. 15 *Cumulative distribution of the errors (difference between the estimated and the calibrated parallel bond strength) for the concrete mixes of the test data set*

4. New scientific results about incorporating unprocessed waste powder materials with normal strength concrete as a cement replacing materials

Where; *CCP – cellular concrete powder; MK – metakaolin; TG – thermogravimetry; SEM – Scanning Electron Microscope*

Nowadays, there is an increasing need for the application of recycled materials in higher amounts in concrete mixes. As a results of the demolition of cellular concrete building components, considerable amount of construction waste is produced. The application of cellular concrete waste in the form of coarse aggregate was studied in the literature in details (Fenyvesi, 2014). However, its application as fine aggregate or supplementary material is a less studied topic (Abed et al, 2019). In my research I have applied cellular concrete powder (CCP) in concrete mixes and subjected the cast specimens to mechanical and durability tests to investigate the effect of CCP. My research demonstrates the following new scientific results:

4.1 I have confirmed through laboratory experiments that recycled cellular concrete in fine powder form can improve the mechanical and durability properties of normal strength concrete (C20/25-C50/60). Based on microstructural analysis I have confirmed that CCP swells during hardening in a cementitious environment. I have confirmed that the magnitude of swelling depends on the CCP particle size and can lead to the formation of microcracks in the matrix. I have confirmed that below d_{max} = 0.09 mm particle size no microcrack formation occurs. I have determined the optimal dosage of CCP (10% (m/m) related to the mass of cement) to achieve the advantages of CCP, *Fig. 16*.

<u>Scientific background:</u>

Previous investigations showed that cellular concrete (e.g. Ytong) powder can be used as a filling material in concrete mixes, that – in limited quantities – is only linearly decreases the strength of concrete (Abed et al, 2019). It was found that this strength decrease is caused by the formation of microcracks due to the swelling of CCP in cementitious environment (Fenyvesi-Jankus, 2015). I have shown that CCP waste in fine powder form with correct dosage can improve mechanical and durability properties of normal strength concrete (C20/25-C50/60), as it is shown in *Fig. 16*. Based on my observations, the application of CCP powder as filling material is a suitable way for recycling [11][12][14][18][19].

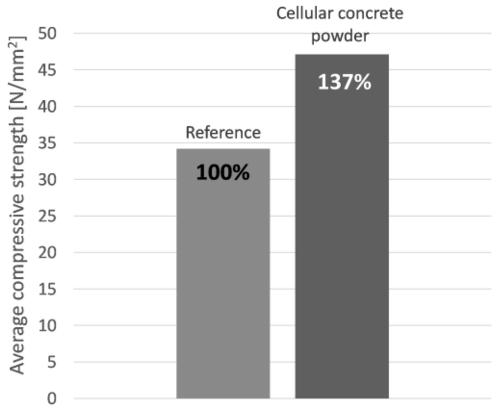

Fig. 16 *Measurement results: average compressive strength of the specimens*

Based on the results of laboratory experiments (TG/DTG/DTA analysis, SEM) I have proved that CCP does not work as a traditional SCM, rather as a filling material. The chemical structure of concrete and CCP are very similar and CCP has high internal porosity. Thus, the new CSH crystals, developing during the hydration of cement matrix, are able to grow amid the already existing CSH crystals of CCP. I have shown that there is no sign of chemical connection between the newly developed CSH crystals and the already existing ones, however, based on the test results, a physical connection can be seen (*Fig. 17*). The analysis of the photos taken by SEM showed that in a cementitious environment during the hardening of concrete CCP is swelling, which in case of higher particle size of CCP leads to microcracks in the cement matrix. However, in case of appropriately small particle size this swelling has a positive effect on the mechanical properties of concrete, because it fills the pores of the concrete. It can be seen on the SEM results (*Fig. 17*) that the small CCP particles work as a filling material, while the larger ones introduce ideal size pores in the concrete. Above that size CCP works as a fine aggregate in the concrete mix, as it was shown in the literature (Abed et al, 2019).

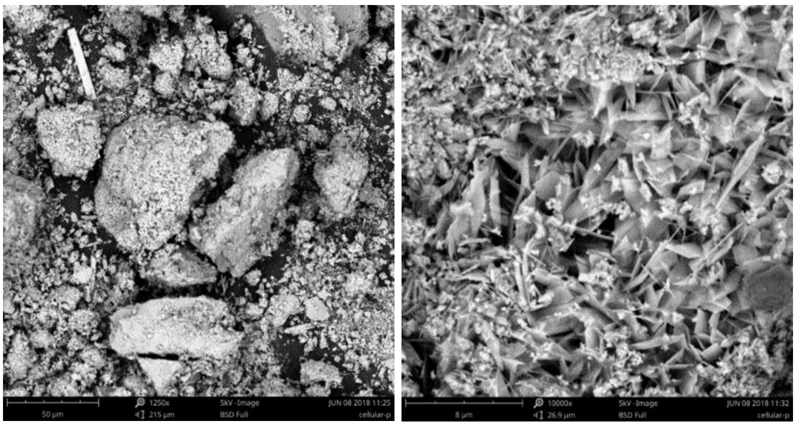

Fig. 17 *SEM of CCP at 1250x (left) and 10000x (right) magnification*

I have proved through laboratory experiments that the maximal size of CCP below which it has positive effect is 0.09 mm (d_{max} < 0.09 mm) and the optimal dosage of CCP can be increased until a given boundary (10% (m/m) related to the mass of cement) to achieve advantageous strength and durability behaviour, above that amount the strength and durability performance of concrete, in which the CCP was applied, starts to deteriorate, in case of normal strength concrete (C20/25 - C50/60), as it can be seen in *Fig. 18*.

However, as the size and amount of pores are decreasing the advantageous effect of CCP is decreasing. I have proved through laboratory experiments that in case of smaller pore sizes in concrete (e.g. in case of high strength concrete), CCP is not able to have positive effect on the strength and durability of concrete. Through laboratory investigations I have proved that in the range of high strength concretes the positive effect of CCP cannot be observed, rather above a certain amount of CCP it has negative effect on the strength and durability properties of HSC, as it can be seen in *Figs. 19***.** In HSC the number and size of pores is lower compared to normal strength concretes. Without the presence of pores the swelling of CCP can lead to microcracks, while in case of too small pore sizes CCP is not able to work as a filling material either [12][14][19].

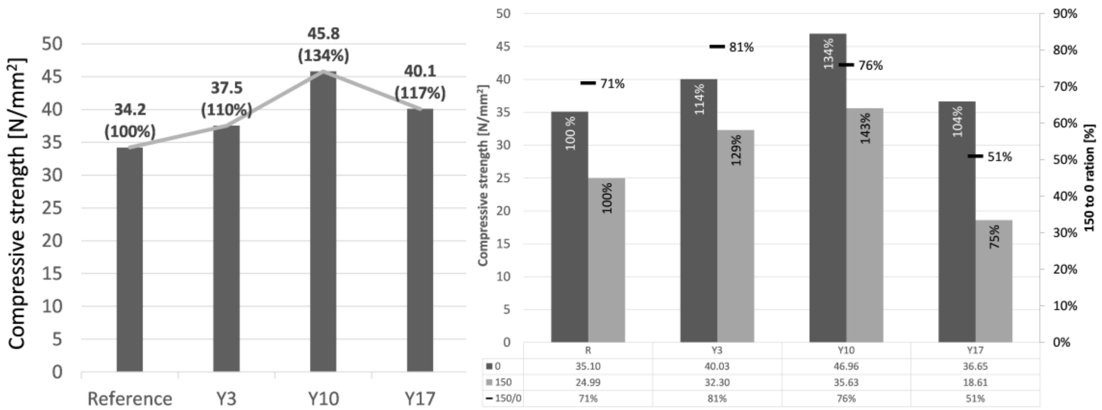

Fig. 18 *Compressive strength of the normal-strength concretes, if cement substituted by CCP in different amounts (left) and frost resistance of the normal-strength concretes containing different amount of CCP after 0 and 150 freezing cycles (right)*

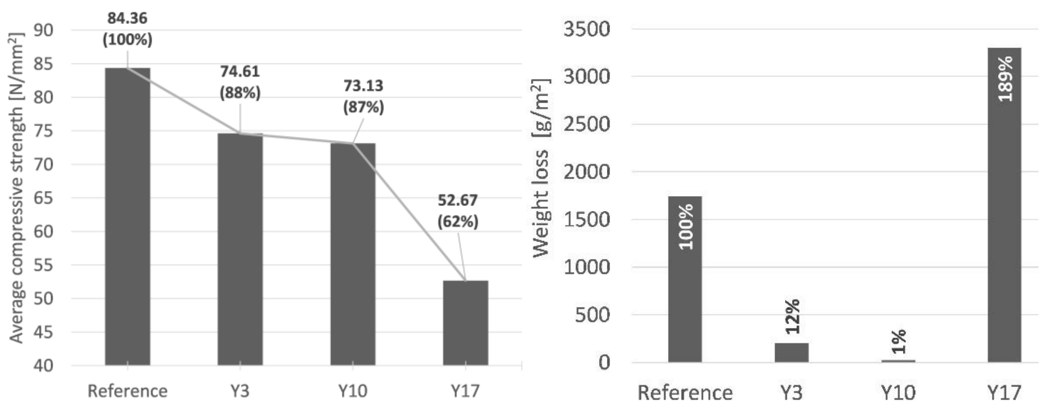

Fig. 19 *Compressive strength (left) and the weight loss after 56 freeze-thaw cycles (right) of the high-strength concretes, if cement substituted by CCP in different amounts*

FUTURE RESEARCH POSSIBILITIES

My thesis can induce a variety of further research possibilities. The topics listed below may be investigated in the future.

1. DEM
    a. Using DEM to model laboratory material testing methods, which require advanced equipment and a lot of preparations, before they can be performed like Young's modulus test or the standard or cyclic pull-out tests. For the latter two solutions are under development by the author of this thesis. The short description of the solution is the following: If the bar can be assumed to be rigid during the test (which is reasonable assumption), it is possible to model the bar either as a clump (rigidly connected spheres), but also (and preferably) as a wall. If a CAD definition of the bar is available, then it could be exported as a STL file (maybe some manipulation will be required to have a manifold data-structure). A fixed velocity could then be imposed on this bar-wall, and the reaction force measured with a history. The issue then will be to use a proper contact model to handle the interaction between the concrete balls and the bar (maybe a custom model shall be developed), as well as use a reasonable resolution to capture the interactions with the "grooves" of the bar. Laboratory measurements have been carried out for the development of that model.
    b. Another DEM related topic which was investigated (laboratory measurement carried out) but not included in higher detail in this thesis is the modelling of lightweight aggregates using DEM.
2. CCP
    a. CCP has been proven to be a waste material, which has the potential to be used additive to concrete. As a next step structural elements (e.g. reinforced concrete girders) shall be cast from concrete (that utilizes CCP) and they shall be tested in various loading cases.

3. Hardness testing

    a. Hardness testing of concretes containing SCMs or waste materials, using DSI test methods. This topic was also covered by the laboratory tests of the author, but the results are not included in this thesis.

    b. Hardness testing of lightweight aggregate concretes. Using different type of lightweight aggregates, it shall be tested that hardness test methods are working on lightweight aggregate concretes or not. This topic was also covered by the laboratory tests of the author, but the results are not included in this thesis.
    c. Based on the loading-unloading curves of the DSI test an expression shall be defined between the Young's modulus or the compressive strength and the total/plastic/elastic energy of the material, which is usable by practicing engineers. Thus using the results of this thesis from the DSI method the compressive strength could be estimated.

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LIST OF PRESENTATIONS

1. *MaMek XII (XII. Hungarian Mechanical Conference), Miskolc University - Miskolc, Hungary, **2015***
2. *Technical Science in the North-Eastern Region of Hungary, University of Debrecen – Debrecen, Hungary **2015***
3. *4th International Conference Contemporary Achievements in Civil Engineering, Faculty of Civil Engineering Subotica, University of Novi Sad, Subotica, Serbia, **2016***
4. *11th fib PhD Symposium in Civil Engineering, Tokyo University, Tokyo, Japan, **2016***
5. *Service life of cement-based materials and structures, COST course, Technical University of Denmark, Lyngby, Denmark, **2016***
6. *International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures (AMCM'2017), Silesian University of Technology (SUT), Gliwice, Poland, **2017***
7. *OATK XI. – National Conference in Material Science, Balatonkenese, Hungary, **2017***
8. *ICEM 2018 International Conference on Experimental Mechanics, Brussels, Belgium, **2018***
9. *8th International Conference on Engineering Failure Analysis (ICEFA VIII), Budapest, Hungary, **2018***
10. *12th fib International PhD-Symposium in Civil Engineering, Czech Technical University, Prague, Czech Republic, **2018***

STANDARDS

EN 197-1:2011 "Cement. Composition, specifications and conformity criteria for common cements".
EN 12390-3:2009 "Testing hardened concrete. Part 3: Compressive strength of test specimens".
EN 14146:2004 "Natural stone test methods. Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency)".
EN 12620:2002 "Aggregates for concrete"
CEN/TS 12390-9:2018 "Testing hardened concrete. Freeze-thaw resistance with de-icing salts, Scaling.".

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