EFFECT OF STANDARD DEVIATION OF CONTACT NORMAL STRENGTH IN DEM FOR CONCRETE

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Summary: *During our research we have investigated the properties of concrete with discrete element method (DEM) to have a better understanding on the processes inside the material. With DEM it is possible to model porous materials (e.g. concrete) on macro level, which requires the setup of different material parameters.*
One of these parameters is the standard deviation of the contact normal strength. This parameter is usually set to 10% based on the recommendation of the software developer company. This parameter value was not exactly developed for concretes, but for other stone-like materials.
In this study the effect of this parameter is investigated from 0% to 100% for concretes with compressive strength varying between C12/16 and C40/50.

Keywords: *discrete element method, concrete, standard deviation, contact normal strength, compressive strength*

1. INTRODUCTION

Discrete Element Method (DEM) is a numerical method, which was developed in the last few decades [1]. The main area of use is the modelling of grains, soil and masonry structures. In case of DEM the material or the structure is modelled with a huge amount of small elements, which are able to move independently from each other until they come into contact [2]. During our research a version of DEM proposed by Peter A. Cundall was used, which is called distinct element method [4]. In this method, any particle that exists is regarded as a rigid element and the behavior of this element is expressed by the equations of motion of extended bodies. A spring is provided between rigid elements which make contact with each other so as to express the interaction of force between them [12]. Then, the equations of motion of each rigid element is solved by numerical integration along the time axis, whereby the behavior of the element is analyzed. The time integration method works with an explicit solver (central difference method). The software that was used during our investigation is called *PFC3D* [8] [9]

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[10]. The solver of this software is using the distinct element method with the following assumptions:

1. The contacts occur over a vanishingly small area (i.e., at a material point).
2. Behavior at the contacts uses a soft-contact approach where the rigid particles are allowed to overlap one another at contact points, and the relative displacements of the two material points forming the contact are considered to reflect the contact deformations which are related to the contact forces.
3. The magnitude of the overlap is related to the compressional component of contact force via the corresponding force displacement law, and all overlaps are small in relation to particle sizes.
4. Bonds (i.e. tension-resisting contacts) can also exist between particles.
5. All particles are spherical. However, the clump logic of PFC supports the creation of super-particles of arbitrary shape: overlapping spheres may be "glued together" to form an irregular particle. Hence, a clump consists of a set of overlapping spherical particles, and behaves as a single rigid body with a deformable boundary.

2. DESCRIPTION OF THE MODELLING OF CONCRETE WITH DEM

In this study concrete cubes with the size of 150×150×150 mm is modelled as test specimen. Concrete is modelled in DEM with a large number of particles (aka. discrete elements). The size of the elements in the model of the concrete block was based on the aggregate sizes found in the real material. In the model, it is intended to approximate the actual particle size distribution found in concrete. The particle size distribution is compiled from the applicable grading limit curves for 32 mm maximum particle size flint aggregate concrete, taking into account the minimum demand of pulp (void volume). It was also intended to investigate concretes with different D_{max}, to see that it cause a difference in the results or not. In this study concretes from three different classes were investigated: C16/20, C45/55 and C50/60. The particle size distribution of the original materials was the following:

Table 1. Particle size distributions of the concrete samples

	Particle size	**Proportion**
C12/16	0/4 mm	40 %
	4/8 mm	22 %
	8/16 mm	38 %
C35/45	0/4 mm	40 %
	4/8 mm	12 %
	8/16 mm	23 %
	16/32 mm	25 %
C40/50	0/4 mm	40 %
	4/8 mm	12 %
	8/16 mm	23 %
	16/32 mm	25 %

During the modelling this distribution was followed by setting up the parameters in *PFC3D*, which is an iteration process. This is the usual solution in case of DEM models during the verification phase [5]. The verification was made with the help of a uniaxial compression test. The detailed description of the parameter setup process can be found in the older publications of the authors of this article. The initial values of the iteration was obtained from the literature. The most important parameters which influences the behavior of the model are the density of the balls, the friction coefficient, as well as the normal strength of the bonds. The bulk modulus of the balls is considered as a constant (it is equal to 1), because the elements are infinitely rigid. The normal strength parameter is given with its mean value and with its standard deviation. In the practice mainly the mean value of the normal strength is changed during the iteration process, while the standard deviation is kept on 10 %, which is the recommendation of the software developer company. In this study the effect of the standard deviation is investigated by a sensitivity analysis.
In the sensitivity analysis the already modelled compression test was applied. During these numerical experiments the compressive strength of the material was measured with the continuous changing of the standard deviation of the normal strength of the contact.

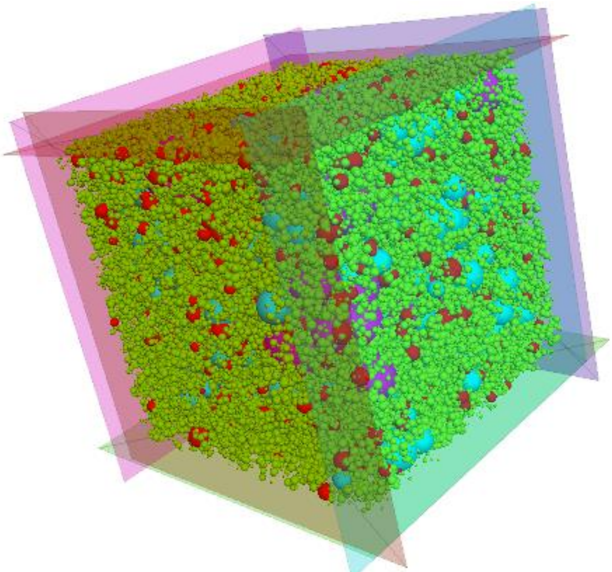

Figure 1. DEM model of a concrete cube

3. VERIFICATION WITH LABORATORY TESTS

To the verification of the models laboratory experiments were conducted, where the compressive strength of the material was measured besides measurement of density and Young's modulus. The selected materials were three different normal strength concrete. The main purpose of choosing this material was to examine a porous solid material, which is commonly used in the building industry. The following table shows the results for the concrete samples:

Table 2. Density and Young's modulus of the concrete specimen

	Density [kg/m^3]	Young's modulus [N/mm^2]	Compressive strength [N/mm^2] (mean value)
C12/16	2258	34578	26.50
C35/45	2254	33223	54.32
C40/50	2379	34783	60.51

Before the tests the specimens were dried to lose their water content which are not in a chemical bonding. For the investigations specimens were prepared, which have the same size and shape. After that these specimens were loaded up to failure with the same loading rate and the maximum force was recorded. During the investigation period the concrete was older than 28 days and it was stored in a dry container until the investigation.

Figure 2. Alpha 3-3000 S hydraulic press with one of the specimen

4. RESULTS OF THE SENSITIVITY INVESTIGATION

Present chapter shows the results of the compression test models that are presented together with the results of the sensitivity analysis. For every investigated concrete type five models were created for every standard deviation values. These models have the same properties except the random arrangement of the particles in the sample. In every case the normal strength was measured and for every standard deviations it was averaged. After that its difference from the real mean value (with 0 standard deviation) was calculated as an absolute value to bo able to analyse the results statistically. The following table shows the results for the C12/16 concrete samples. The differences are shown in N/mm^2 and in percentage too.

Table 3. Results of the sensitivity analysis (C16/20)

C12/16	Standard deviation of the strength of the parallel bonds (pb_coh_sdev) [%]	Average normal strength of the material [N/mm^2]	Difference from mean value [N/mm^2]	Difference from mean value [%]
	0	**26,50**	0	0
	1	**26,36**	0,14	0,53
	10	**26,16**	0,34	1,28
	20	**25,26**	1,24	4,68
	30	**24,42**	2,08	7,85
	40	**24,48**	2,02	7,62
	50	**24,30**	2,20	8,30
	70	**26,08**	0,42	1,58
	100	**28,44**	1,94	7,32

The behavior for the different types of conrete were very similar as it can be seen on *Figure 3*. It can be seen on the figure that with the increase of the standard deviation the difference of the compressive strength of the samples also increases.

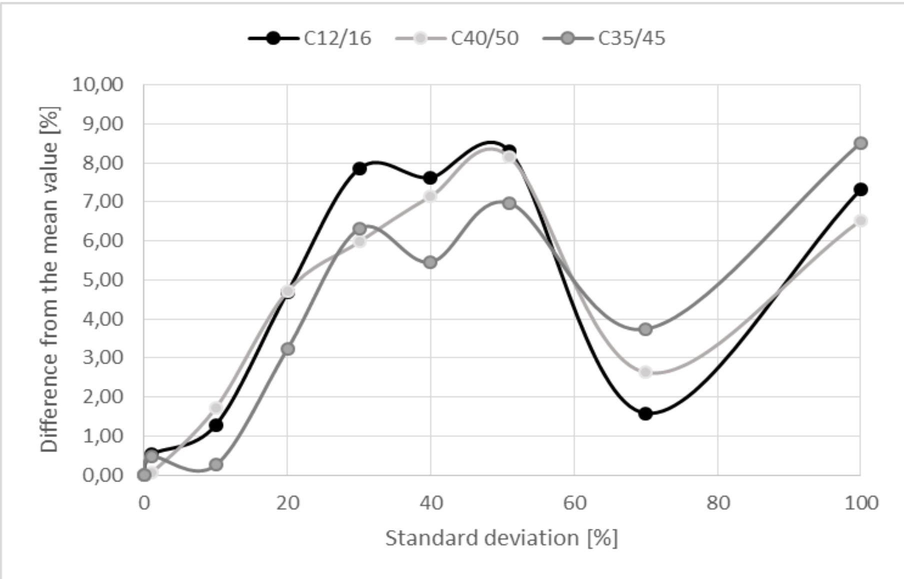

Figure 3. Difference from the mean value in function of the standard deviation

This is valid only until the standard deviation reaches a given value (around 50 %), after that a decrease was observable for all concrete samples. It is important to mention that until 50% the differences are increasing on the safe side of the mean value. In case of 100% standard deviation the difference is again higher, than it was in case of 70%. It is not clearly undertood until now, why this decrease in the results appeared. It has to be mentioned that all the values in difference were under 9%, which can be considered as significant difference. However if we keep the value of standard deviation under 10% then a very small difference can be observed, but the measurements becomes more realistic. In real measurements there is also a small difference in the results. In case of the modelling if we choose the value of standard deviation to 0 then always the same result appers, which is unrealistic. Based on these investigations it is recommended to use a given value of standard deviation for the modelling of concrete, however it should be chosen under 10%.
It is also worth to mention that not only the final results but the characteristics of the compression tests are very similar for the laboratory and numerical investigations as it can be seen on Figure 3. The curve from the model behaves quite similarly to the typical concrete stress-strain curves. As a difference it can be seen, that at the initial stage of the curve a kind of “waves” can be observed. Contrary in case of the real test, this stage is linear. This phenomenon can be originated from the sturcture of the DEM model, which is built up from elements and bonds. In this initial part of the test a minor particle rearrangement can be observed, which cause this type of behavior of the models.

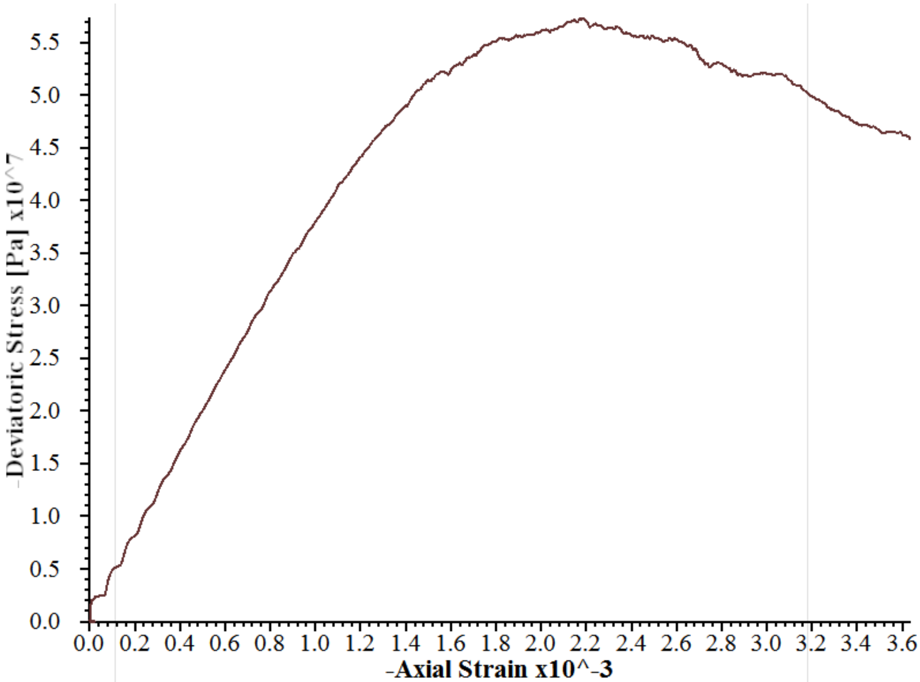

Figure 4. Stress-strain diagram of one of the samples

5. CONCLUSION

In this study the effect of standard deviation was investigated for the discrete element modelling of concrete. The model of the material was aimed to follow the real particle size distribution of the samples. The results of the compression tests showed a very similar behavior to the laboratory tests both in results and in characteristics too. Based on the results of the sensitivity analysis it can be concluded that the standard deviation of the normal strength of the contacts can have a significant effect, however if it is chosen under a certain value (around 10-20%) it can give the behavior of the compressive strength test a more realistic nature. It can be seen on the model results that until 50% standard deviation the results always remain on the safe side. It is planned in the future to investigate the effect of standard deviation between 0 and 20% on a more detailed way, because the results of present paper shows that the optimal value of standard deviation is in that range.

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REFERENCES

[1] Bagi, K.: The Discrete Element Method. *Lecture notes,* **2007**, Budapest University of Technology and Economics. 73 p. (in Hungarian)
[2] Bagi, K.: An algorithm to generate random dense arrangements for discrete element simulations of granular assemblies. *Granular Matter,* **2011**, 25:1159-1166
[3] Bagi, K.: Fundaments of the discrete element method. *Lecture notes*, **2012**, Budapest University of Technology and Economics
[4] Cundall, P.A.: A computer model for simulating progressive large scale movements in blocky rock systems. *Procs. Symposium of the International Society of Rock Mechanics,* **1971**, 1:Paper II-8
[5] Cundall, P.A.: Formulation of a three-dimensional distinct element model – Part I: A scheme to detect and represent contacts in a system composed of many polyhedral blocks. *Int. J. Rock Mech. Min. Sci. & Geomech*, **1988**, Abst. 25:107-116
[6] Fisher-Cripps, A.: Introduction to Contact Mehanics. *Springer*, **2000**, 221p.
[7] Hertz, H.: Über die Berührung fester elastischer Körper. *Journal für die reine und angewandte Mathematik*, **1881**, Vol. 5. pp. 12-23. 1881
[8] Itasca Consulting Group: 3 Dimensional Distinct Element Code. *Users Guide,* **2007**, Minneapolis. Minnesota. USA
[9] Itasca Consulting Group: Particle Flow Code in Three Dimensions. *Users Guide,* **2008**, Minneapolis. Minnesota. USA
[10] Itasca Consulting Group: Universal Distinct Element Code. *Users Guide*, **2011**, Minneapolis. Minnesota. USA

[11] Kanou, S., Amano, M., Terasaka, Y., Matsumoto, N., Wada, T.: Terra-mechanical simulation using distinct element method. *Komatsu Technical Report*, **2003**, Vol. 49. No. 151. pp. 13–19.
[12] O'Sullivan, C.: Particulate discrete element modeling. *Spoon Press*, **2011**, Abingdon

UTICAJ STANDARDNE DEVIJACIJE NORMALNE KONTAKTNE ČVRSTOĆE U MDE U BETONU

***Rezime**: Tokom naših istraživanja svojstva betona, radi boljeg razumevanja procesa unutar materijala koristili smo metodu diskretnih elemenata (MDE). Sa MDE je moguće modelirati porozne materijale (npr. beton) na makro nivou, sa podešavanjem različitih parametara materijala. Jedan od ovih parametara je standardna devijacija normalne kontaktne čvrstoće. Ovaj parametar je obično postavljen na 10% na osnovu preporuke kompanije koja razvija softver. U radu je uticaj ovog parametra ispitivan od 1% do 100% za betone sa klasom čvrstoće pri pritisku između C25 / 30 do C55 / 67.*

***Ključne reči:** metoda diskretnih elemenata, beton, standardna devijacija, normalna kontaktna čvrstoća, čvrstoća pri pritisku*