DOI: https://doi.org/10.14256/JCE.2424.2018

Građevinar 8/2020

Primljen / Received: 25.4.2018.
Ispravljen / Corrected: 3.10.2018.
Prihvaćen / Accepted: 15.3.2019.
Dostupno online / Available online: 10.9.2020.

Performance based simulation of pervious concrete using discrete element method

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Research paper

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Performance based simulation of pervious concrete using discrete element method

Pervious concrete is a special type of concrete that differs from ordinary concrete by its highly porous nature, which is why this type of discrete material can not be modelled using the Finite Element Method (FEM). Behaviour of pervious concrete samples with different aggregate sizes and void ratios is simulated in the paper, using the Particle Flow Code (PFC) software, which is based on the discrete element method (DEM). The PFC software is used to simulate various experimental results obtained on high paste content pervious concrete samples.

Key words:
pervious concrete, stress-strain, discrete element method, particle flow code

Prethodno priopćenje

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Simulacija ponašanja procjednog betona pomoću metode diskretnih elemenata

Procjedni beton je posebna vrsta betona koji se od običnog betona razlikuje izrazitom poroznošću, zbog čega se ta vrsta diskretnog materijala ne može modelirati pomoću metode konačnih elemenata (FEM). U radu se simulira ponašanje uzoraka procjednog betona s različitim frakcijama agregata i koeficijentima pora, a za te se potrebe koristi računalni program Particle Flow Code (PFC) koji se temelji na metodi diskretnih elemenata (DEM). Pomoću programa PFC simuliraju se različiti eksperimentalni rezultati dobiveni na uzorcima procjednog betona s visokim udjelom cementne paste.

Ključne riječi:
procjedni beton, naprezanje-deformacija, metoda diskretnih elemenata, mehanizam protoka čestica

Vorherige Mitteilung

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Simulation des Verhaltens von durchlässigem Beton mit der Diskrete Elemente Methode

Durchlässiger Beton ist eine spezielle Betonart, die sich von gewöhnlichem Beton durch ihre ausgeprägte Porosität unterscheidet, weshalb diese Art von diskretem Material nicht mit der Finite-Elemente-Methode (FEM) modelliert werden kann. Die Arbeit simuliert das Verhalten von durchlässigen Betonproben mit unterschiedlichen Aggregatanteilen und Porenkoeffizienten und verwendet das Computerprogramm Particle Flow Code (PFC), das auf der Diskrete Elemente Methode (DEM) basiert. Mit dem PFC-Programm werden verschiedene experimentelle Ergebnisse simuliert, die an durchlässigen Betonproben mit einem hohen Gehalt an Zementpaste erhalten wurden.

Schlüsselwörter:
durchlässiger Beton, Spannungs-Dehnungs-Methode, Diskrete Elemente Methode, Partikeldurchflussmechanismus

1. Introduction

Pervious concrete is an eco-friendly material that is not only strong enough but also exhibits high porosity (15 % to 25 %). Due to this special property it is becoming popular in construction industry, principally in pavements and green houses [1-3] In pavement construction, pervious concrete has been found to be very useful due to various benefits like reduction in storm water runoff, ground water recharge, reduction in atmospheric temperature, reduction in surface runoff, etc. [1-4]. Due to its many benefits, pervious concrete is gaining in popularity in pavement sector. Presence of interconnecting pores in concrete permits the water to flow through it and, hence, helps in the recharge of ground water table, which is one of major benefits of pervious concrete [4]. Pervious concrete has been found to be an important tool in balancing environmental impact due to urbanization, and has been chosen as one of the best management practices by the U.S. Environmental Protection Agency (EPA) [1].

Due to porous nature and environmental benefits of pervious concrete, it is also called porous concrete or gap-graded concrete [4]. Pervious concrete is the opposite to ordinary concrete, where porosity needs to be minimised for better performance, although some minimum porosity is nevertheless required for successful performance. Previous studies have shown that porosity and strength are inversely proportional to each other and, hence, a perfect combination of strength and porosity is required in the production of pervious concrete. Various factors such as the water-cement ratio (W/C), size of aggregates, aggregate-cement ratio (A/C), method and level of compaction, and use of additional admixtures, play an important role in the performance of pervious concrete [4-13].

Behaviour of pervious concrete is different from ordinary concrete due to presence of many small pores that allow water passage. The performance of pervious concrete has been evaluated in a number of studies by using a variety of combinations of W/C ratio, A/C ratio, use of admixtures, etc. [8-12]. The stress-strain behaviour of various aggregates sizes and A/C ratios has been studied by many researchers to gain better understanding of the behaviour of pervious concrete [13-16].

The present study focuses on the performance-based simulation of pervious concrete by using stress-stress relationship of various types of aggregates and various levels of cement content. The present work continues on the experimental study of pervious concrete samples conducted by Deo and Neithlath (2011) [14] by using the Discrete Element Method (DEM) based computer software named Particle Flow Code (PFC). Stress-strain plots of various types of pervious concrete samples are simulated in the paper using the PFC. The results demonstrate the effectiveness of the PFC on various samples, and so the PFC can be utilised as an effective tool in future performance based studies.

2. Discrete element method

The Discrete Element Method is a granular based method that has been developed to simulate the micromechanical behaviour of non-cohesive media such as sand and soil. Particles are statically modelled using rigid spheres (in 3D) or discs (in 2D) of varying diameters. As rigid spheres or discs are connected to each other at their contact points, these contacts are assigned the stiffness (normal and shear) and coefficient of friction values. The commercially available PFC code is based on the DEM, which is an extension of particle based programmes BALL and TRUBAL suggested by Cundall & Strack [17]. These programmes can simulate behaviour of solid rocks using cohesion bond at their contact points. The model used is called the bonded particle model (BPM) for solid rocks. The BPM can be used to estimate the propagation and fracturing of cracks by simulating bond breaking.

The PFC model uses two types of bonds: contact bonds and parallel bonds (Figure 1.) [18]. The contact bond uses an elastic spring with constant normal (Kn) and shear stiffness (Ks) that can only transfer forces at contact points, while on the other hand the parallel bond model resists rotation of particles by using a set of elastic springs at the plane of contact. The parallel bond can resist the moment produced during particle rotation; this resistance is operated through a series of elastic springs evenly distributed over a small size section at the plane of contact [19]. These bonded models can mimic mechanical performance of bonded materials like cement between neighbouring particles.

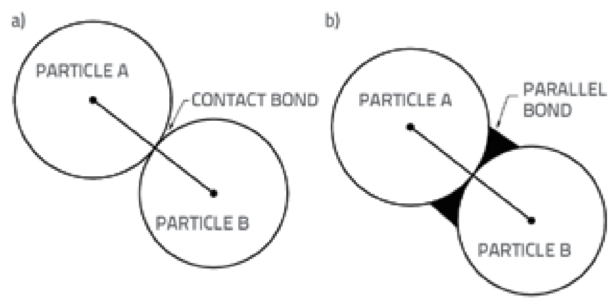

Figure 1. Contact bond / parallel bond

Pervious concrete is composed of granulated material structured in such a way that its different components are not connected to each other at material level [6]. Hence, the DEM is one of the best choices for modelling such type of material [20, 21]. The DEM based programme PFC is used to simulate the stress-strain behaviour of pervious concrete with various aggregate sizes and cement contents under uniaxial compressive load. The stress-strain behaviour of various samples is plotted and compared with experimental stress-strain plots of pervious concrete specimens.

3. PFC model setup

As the main objective of the present study is to simulate the stress-strain behaviour of pervious concrete using the PFC, it is necessary to generate the same size of aggregates and bond property between the particles. The stress-strain behaviour of concrete mainly depends on the grade of concrete which in turn depends on the size of aggregate, shape of aggregate, gradation of aggregates, water-cement ratio, and aggregate cement ratio. So a two stage procedure has been adopted to model pervious concrete specimens:

- Physical modelling
- Performance modelling.

Physical modelling refers to modelling physical components of the pervious concrete mix while performance modelling involves modelling properties that influence performance of the pervious concrete mix.

Various types of mix and their properties have been modelled using Fish Tank, which is provided by PFC to model various types of materials and their testing. Fish Tank is a group of programmes supplied by PFC which reduces modelling efforts [18]. Various types of testing procedures for materials are also provided in the supplied Fish Tank program.

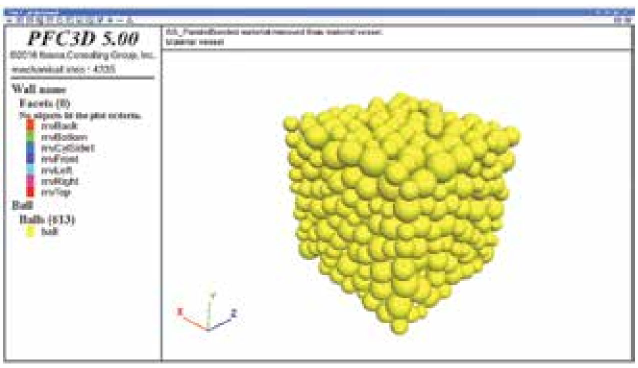

Figure 2. Pervious concrete cube PFC model

Cubes from various pervious concrete mixes (Figure 2) are modelled in this research using Fish Tank; aggregates are modelled as per actual size and gradation and are tested under unconfined compressive load; stress-strain plots have been generated.

4. Material genesis

Pervious concrete samples were generated in PFC as per material property and void ratio; all materials were assigned various parameters depending on the grading of aggregates and cement paste properties. A group of experiments were performed by Deo and Neithlath [14] for varying aggregate types, cement contents, and voids ratios. Based on their experimental details, appropriate PFC models were prepared using parallel bonds, and the results were then compared. As already discussed, the two stage modelling was implemented using PFC.

4.1. Physical modelling

Main features included in physical modelling are presented in this section.

4.1.1. Aggregates size and grading

The concrete was modelled with large number of spherical discrete elements. Diameters of these elements were based on the actual aggregate size and grading data as registered in real materials. The diameter and grading of aggregates were modelled with reference to the actual material aggregate size and grading data. Three different sizes of aggregates were used in PFC models:

a) M-1: 12.5 mm (1/2''),
b) M-2: 9.5 mm (3/8''),
c) M-3: 4.75 mm (#4).

Table 1. Size of aggregates and void ratio

Name of sample	Mix	Agreggate size		Fine aggregate	Void ratio (Ø)
		Passing [mm]	Retained [mm]		
M-1-1	M-1 12.5 mm (1/2'')	25	12.5	0	0.19
M-1-2					0.22
M-1-3					0.27
M-2-1	M-2 9.5 mm (3.8'')	12.5	9.5	0	0.19
M-2-2					0.22
M-2-3					0.27
M-3-1	M-3 4.75 mm (#4)	9.5	4.75	0	0.19
M-3-2					0.22
M-3-3					0.27

The aggregate grading curve is shown in Figure 3. No fine aggregates were used in this study.

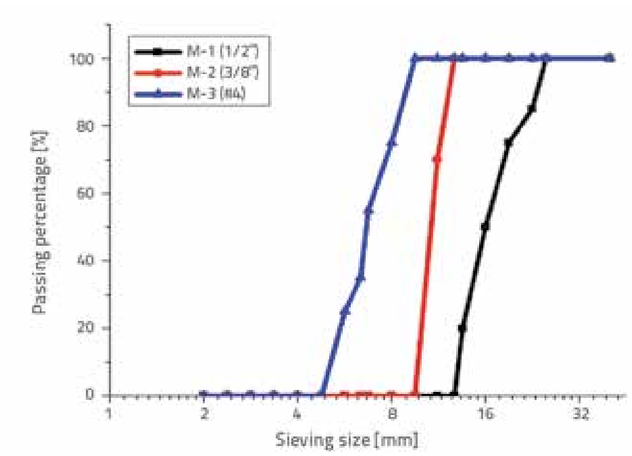

Figure 3. Aggregate size grading curve

Aggregate sizes and void ratios of three types of mixes are summarised in Table 1. All nine models were generated based on the actual material gradation and void ratio. A total of nine models were generated and modelled in PFC. The results obtained were compared with experimental results.

4.1.2. Void ratio

Void ratio can be incorporated in the PFC model. A modified void ratio was taken into consideration so as to take the effect of cement paste into consideration. In PFC, virtual model effect of cement paste was directly assigned to parallel bond properties; hence no cement paste was modelled separately. As cement paste was not modelled separately, the effect of void ratio was incorporated in the PFC model. PFC calculates the void ratio based on grain size distribution (see Eqn. (7) below). A modified void ratio value is suggested here to incorporate the effect of cement paste into the pervious concrete matrix. Based on the actual void ratio, the PFC model assigned a modified value of void ratio. The following expression (9) shows the modified value of void ratio. The basic expression for void ratio is:

$$Ø = Vv/V \quad (1)$$

$$Vv = V - (Va + Vp) \quad (2)$$

The volume of paste is:

$$Vp = Vc + Vw \quad (3)$$

where is the volume of water and can be neglected as it is very small.

Hence, the Eqn. (3) is re-written as follows:

$$Vp = Vc \quad (4)$$

Aggregate cement ratio is:

$$A/C = Va / Vc$$

$$Vv = V - (Va + Vc) \quad (5)$$

From Eqn. (1). and Eqn. (2) we have:

$$Ø = (V - (Va + Vc)) / V$$

Rearranging the terms:

$$Ø = 1 - (Va (1 + C/A)) / V \quad (6)$$

In PFC, only aggregates are present in the mix and hence:

$$Vv (PFC) = V - Va \quad (7)$$

As per Eqn. (6) the volume of paste is not included in the calculation of void ratio in PFC, and hence,:

$$Ø (PFC) = (V - Va)/V = 1 - Va/V \quad (8)$$

Thus we have:

$$Va/V = Ø (PFC) + 1$$

From Eqn. (6):

$$Ø (PFC) = 1 - [(Ø (PFC) + 1) \cdot (1 + C/A)]$$

Hence:

$$Ø (PFC) = 1 - [(1 - Ø) / (1 + C/A)] \quad (9)$$

where:
Ø - void ratio,
Vv - volume of void,
Va - volume of aggregate,
Vc - volume of cement,
A/C - aggregate/cement ratio,
C/A - cement/aggregate ratio
V - total volume of sample/ container.

Eqn. (9) gives a relationship between an actual void ratio and the PFC value. Using the relationship given in Eqn. (9) the void ratio was calculated (Table 2) and assigned to the corresponding PFC models.

Table 2. C/A ratio and corrected void ratio

Name of sample	Mix	C/A ratio	Void Ratio (Ø)	Corrected void ratio Ø according to PFC
M-1-1	M-1 12.5 mm (1/2")	0.40	0.19	0.42
M-1-2		0.36	0.22	0.43
M-1-3		0.31	0.27	0.44
M-2-1	M-2 9.5 mm (3.8")	0.42	0.19	0.43
M-2-2		0.37	0.22	0.43
M-2-3		0.30	0.27	0.44
M-3-1	M-3 4.75 mm (#4)	0.45	0.19	0.44
M-3-2		0.38	0.22	0.44
M-3-3		0.32	0.27	0.45

4.2. Performance modelling

Performance modelling can be achieved in PFC by proper selection of controlling parameters that are responsible for the performance of pervious concrete, and are ultimately based on internal properties of cement paste and its behaviour [18]. Performance of pervious concrete mainly depends on the cement paste properties, which in turn affects its behaviour. So a proper assignment of parameters is important to model the effect of cement paste. Parallel bond parameters were selected based on actual material properties. The following parameters were assigned to various models:
- Bulk modulus
- Friction coefficient

Properties of the bond between cement and aggregates were modelled using parallel bond in PFC, for which following parameters were given:
- mean value of normal strength
- standard deviation of normal strength
- mean value of shear strength
- standard deviation of shear strength
- stiffness ratio of parallel bonds.

FISH-Tank programs were modified as per material property, water to cement ratio, aggregate cement ratio, and other properties of materials.

5. Material testing

Material testing can be performed in PFC using the predefined program FISH-Tank, which provides facility for testing materials under tension and compression (confined and unconfined). Various plots can be generated based on the user's requirement like stress-strain, load-deflection, etc. Strain rates were controlled by a special PFC function called servomechanism. This servomechanism helps to control the moving wall velocity to maintain specified stress in PFC [18].
All models generated in PFC (Figure 4.) were tested under unconfined uniaxial compressive loads at the constant strain of 0.15, and stress-strain plots were generated. Models were given a controlled rate of strain using the servomechanism function in PFC. Figure 4 shows a systematic view of the model generated in PFC and tested under compressive load in unconfined conditions. As the load to the model increases, the bonds between the particles fail (Figure 5.), which in turn develops cracks in the sample and, ultimately, the sample fails.

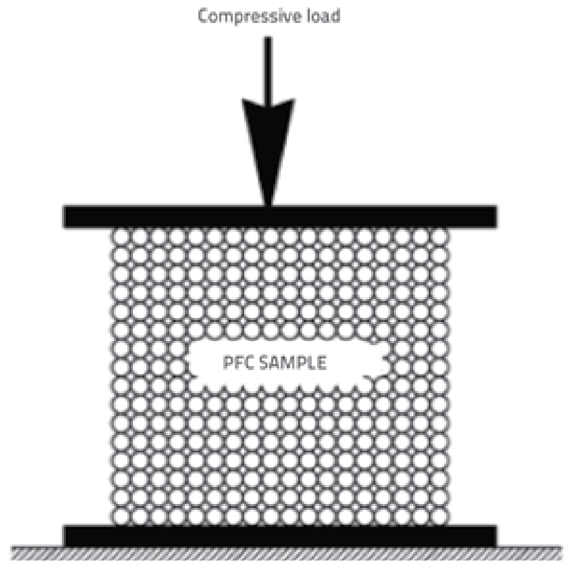

Figure 4. Testing of sample

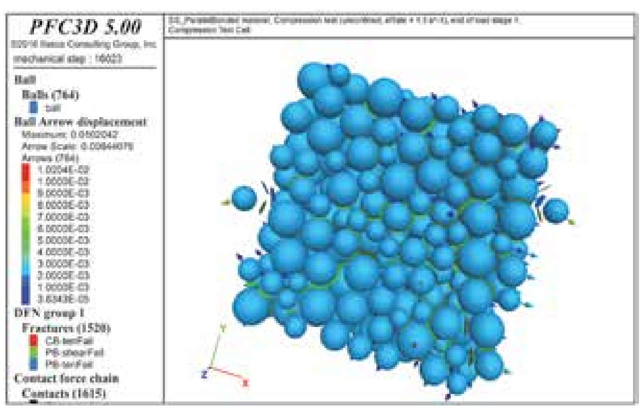

Figure 5. Failure of bonds.

6. Results and discussion

The uniaxial compression and stress-strain behaviour simulation were performed to compare mechanical behaviour of virtual PFC models with experimental results. Three different types of pervious concrete mix with aggregated gradings were generated. Each mix was modelled with three void ratios, and the total of nine models were generated. Model parameters were adjusted based on aggregate grading and void ratio. PFC virtual model results and the corresponding experimental results were verified as reported by Deo and Neithlath (2011) [14].

6.1. Peak stress simulation under uniaxial compression

It can be seen from Table 3 that all nine models closely reproduce the peak stress and the corresponding strain at peak stress. The maximum percentage error in peak stress amounted to 13.85 % in sample M-2-1, while average percentage errors in PFC model when compared to experimental results were 0.79 %, 9.5 %, and 3.78, in samples M-1 to M-3, respectively.

Similarly, strain values at peak stress were close to experimental values in all samples. The maximum percentage error amounted to 15.8 % in sample M-3-2, while average percentage errors observed in mixes M-1, M-2, and M-3 amounted to 3.33 %, 5 % and 10.34, respectively.

6.2. Stress-strain behaviour under uniaxial compression

PFC models were tested under uniaxial unconfined compression loading, and stress-strain plots were generated. It can be seen that the response of sample M-1-1 (Figure 6.a) in the initial stage before peak stress matches the experimental response but, after peak stress, the stress-strain behaviour differs from the experimental plot. This may be due to breaking of bonds in PFC model and parameters assigned to model. Similar patterns were observed in sample M-1-2 and M-1-3 (Figures 6.b, 6.c).

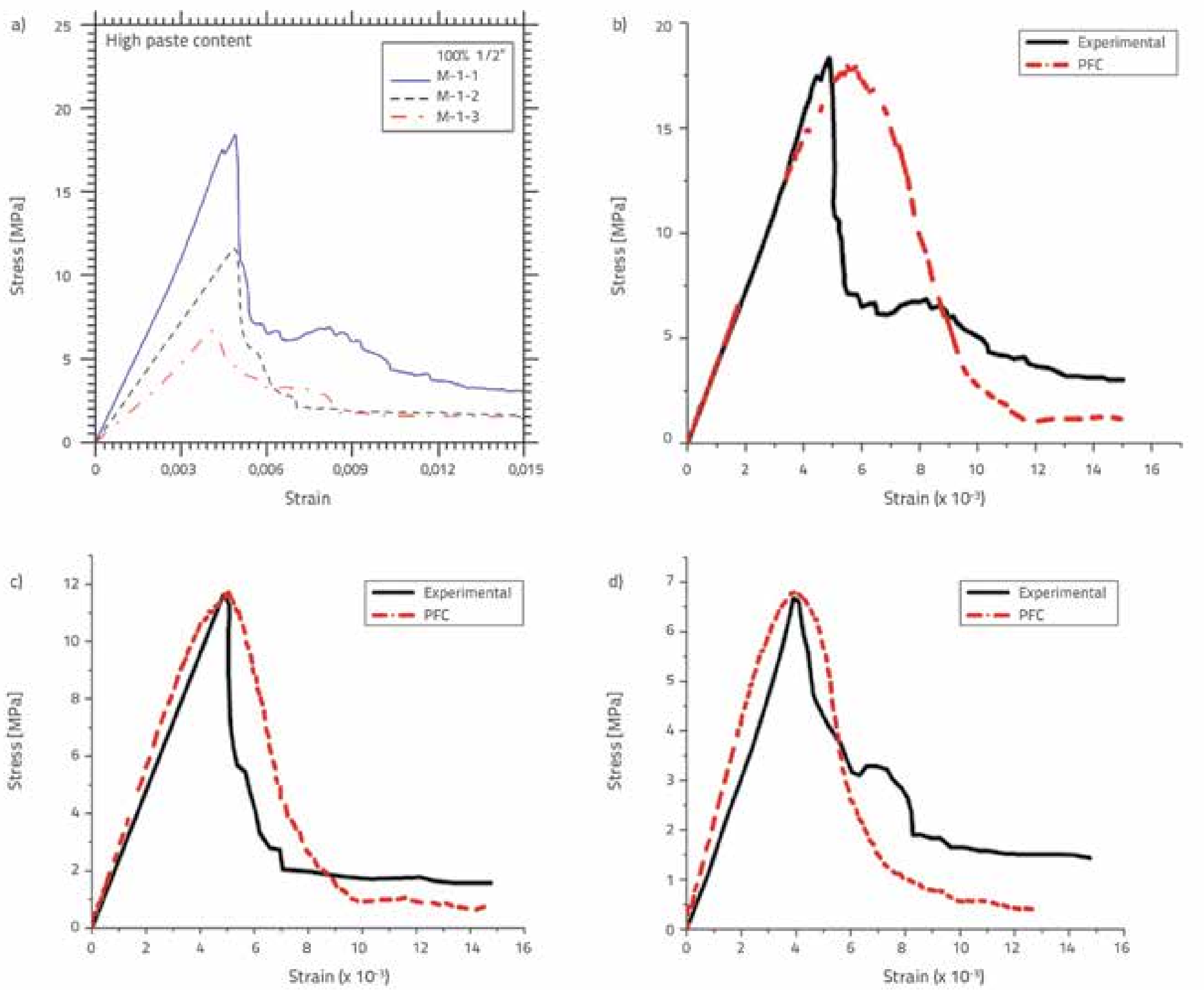

Figure 6. Experimental & PFC plots for mix M-1: a) Experimental plot for Mix M-1, according to [14]; b) PFC and experimental stress-strain plot for M-1-1; c) PFC and experimental stress-strain plot for M-1-2; d) PFC and experimental stress-strain plot for M-1-3

Table 3. Strain at peak stress in experimental and PFC plot

Name of sample	Mix	Peak stress achieved [MPa]		Error [%]	Average error [%]	Strain at peak stress (x 10^{-4})		Error [%]	Average error [%]
		Experiment	PFC			Experiment	PFC		
M-1-1	M-1	18	18	0	0.79	50	55	10	3.33
M-1-2		11.6	11.7	0.86		50	50	0	
M-1-3		6.7	6.8	1.5		40	40	0	
M-2-1	M-2	19.5	22.2	13.85	9.5	60	63	5	5
M-2-2		14.3	14.5	1.4		55	55	0	
M-2-3		9.8	8.5	13.27		50	45	10	
M-3-1	M-3	22	23	4.54	3.78	66	63	4.54	10.34
M-3-2		15.8	15.6	1.26		65	55	15.38	
M-3-3		9	8.5	5.55		45	40	11.11	

It can be seen from the stress-strain plot of Mix M-2 (Figure 7) that the PFC plot behaviour is similar to that of the experimental plot. However, a slight variation was observed in sample M-2-1, which may be due to the assigned property of parallel bond and size of aggregates.

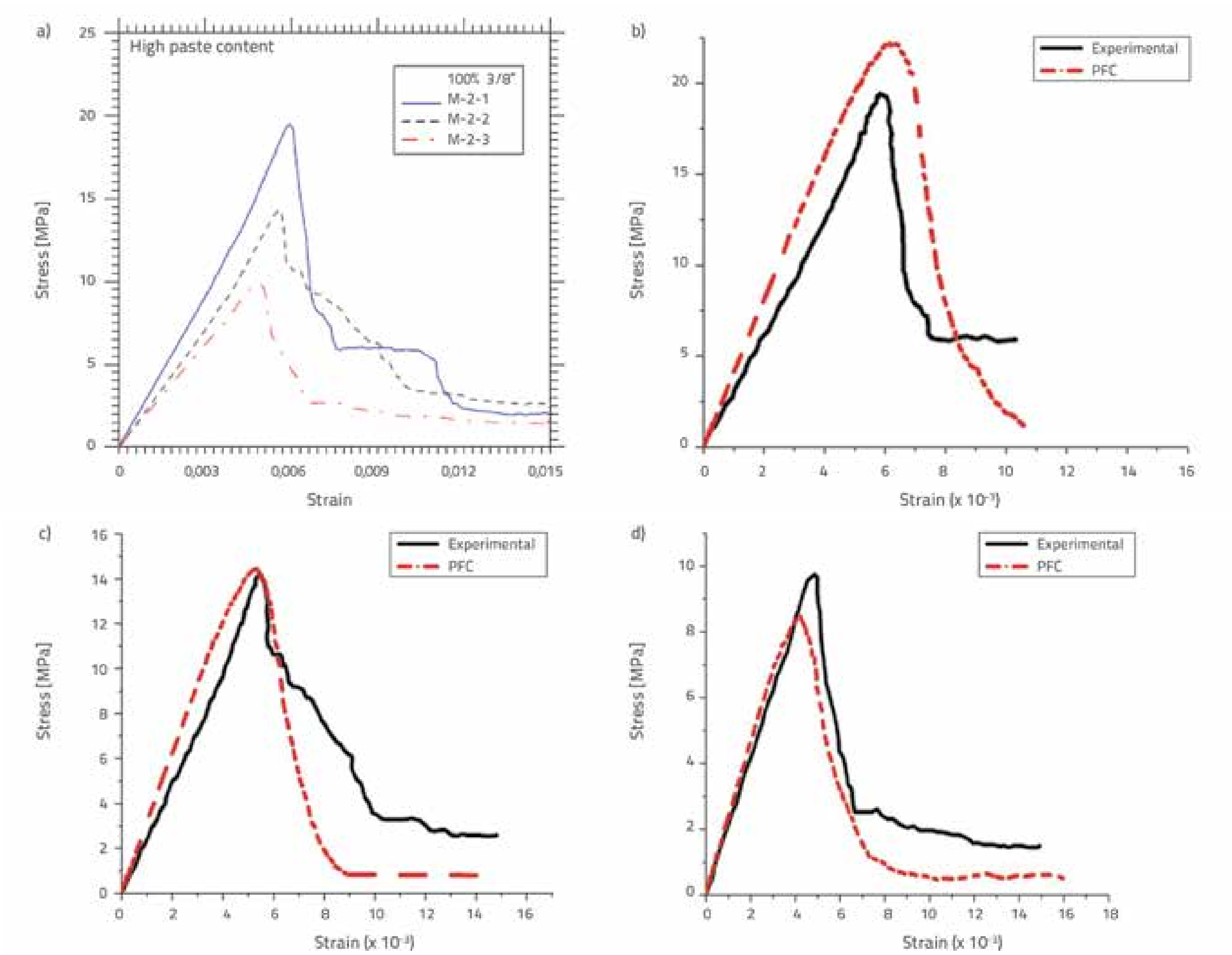

Figure z. Experimental & PFC plots for mix M-2: a) Experimental plot for Mix M-2, according to [14]; b) PFC and experimental stress-strain plot for M-2-1; c) PFC and experimental stress-strain plot for M-2-2; d) PFC and experimental stress-strain plot for M-2-3

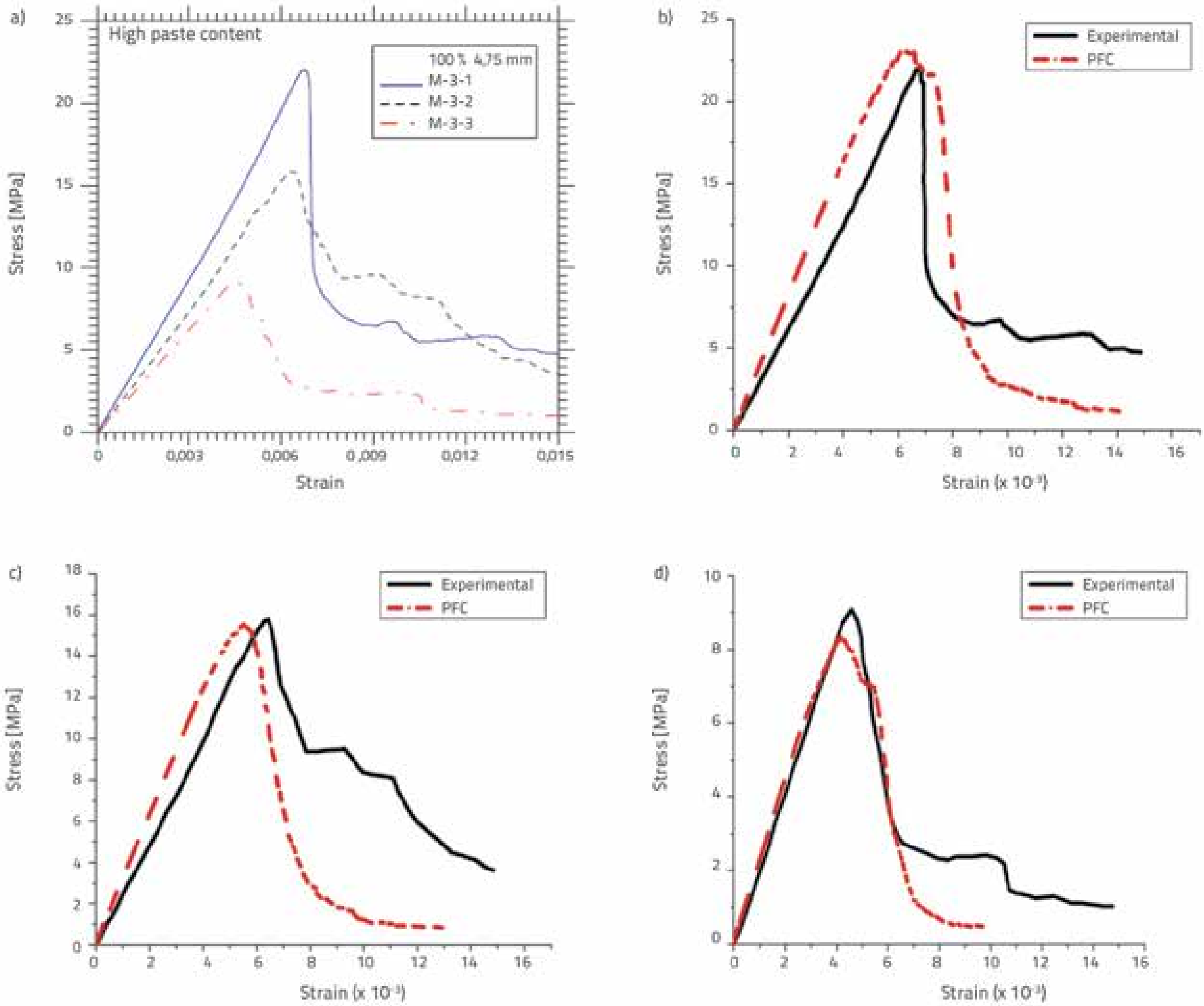

Figure 8. Experimental & PFC plots for mix M-3: a) Experimental plot for Mix M-3, according to [14]; b) PFC and experimental stress-strain plot for M-3-1; c) PFC and experimental stress-strain plot for M-3-2; d) PFC and experimental stress-strain plot for M-3-3

It was observed that the stress-strain performance in Mix M-3 (Figure 8.) after peak stress differs from the experimental plot. The plot of sample M-3-1 is slightly higher than that of the experimental plot (Figure 8.a). Responses of samples M-3-2 and M-3-3 nearly match the experimental plot. A close observation of response shows that, after peak stress, strain values do not match the experimental response. This may be due to breaking of parallel bonds in PFC model.

7. Conclusion

Based on the above results, it can be concluded that the Discrete Element Method (DEM) is an effective tool for obtaining performance of discrete types of materials like pervious concrete and, after proper set up of parameters, the model can lead to results that are strongly correlated to real laboratory test observations.

It is further concluded that the maximum compressive strength as well as the stress-strain response of pervious concrete can be reproduced with reasonable accuracy with the help of the DEM based PFC software. Statically reasonable results can be obtained without the need for laboratory tests, which may add to better understanding of material behaviour.

The results obtained in this paper show that the PFC virtual model can produce good results, comparable to those obtained in real material tests. Therefore, with the help of these results a better understanding of material can be achieved.

REFERENCES

[1] ACI, Report on Pervious Concrete, MI: American Concrete Institute, 2010.

[2] NMRCA-Concrete in Practice-38 (CIP-38): National Ready Mix Concrete Association (NMRCA).

[3] Haselbach, L.M., Valavala, S., Montes, F.: Permeability predictions for sandclogged Portland cement pervious concrete pavement systems, J. Environ. Manage. (Elsevier), 81 (2005), pp. 42-49.

[4] Tennis, P.D., Leming, M.L., Akers, D.J.: Pervious concrete pavements, Skokie, Illinois & Silver Spring, Maryland, Portland Cement Association & National Readymixed Concrete Association, 2004.

[5] Gafoori, N., Shivaji D.: Laboratory investigation of compacted no-fines concrete for paving materials, Journal of Materials in Civil Engineering, 7 (1995) 3, pp.183-191.

[6] McCain, G.N., Dewoolkar, M.M.: Strength and permeability characteristics of porous concrete pavements, Transp. Res. Board, pp. 1-13, 2009.

[7] Kevern, J.T., Wang, K., Schaefer, V.R. : Effect of coarse aggregate on the freeze- thaw durability of pervious concrete, J. Mater. Civ. Eng., 22 (2010) 5, pp. 469-475.

[8] Jain, A.K., Chouhan, J.S.: Effect of shape of aggregate on compressive strength and permeability properties of pervious concrete, Int. J. Adv. Eng. Res. Stud., 1 (2011), pp. 120-126.

[9] Chindaprasrit, P., Hatanaka, S., Chareerat, T., Mishima, N., Yuasa, Y.: Cement paste characteristics and porous concrete properties, Construction and Building Materials, 22 (2008), pp. 894-901.

[10] Huang, B., Xiang, S., Hao, W., Burdette, E.G.: Laboratory evaluation of permeability and strength of polymer-modified pervious concrete, Construction and Building Materials, 24 (2010), pp. 818-823.

[11] Ibrahim, A., Enad M., Mohammed, Y., Chowdary, V.: Experimental study on Portland cement pervious concrete mechanical and hydrological properties, Construction and Building Materials, 50 (2014), pp. 524-529.

[12] Yahia, A., Daddy, K.K.: New approach to proportion pervious concrete, Construction and Building Materials, pp. 38-46, 2014.

[13] Yang, J., Jiang, G.: Experimental study on properties of pervious concrete pavement materials, Cement and Concrete Research, 33 (2003), pp. 381-386.

[14] Deo, O., Narayanan, N.: Compressive response of pervious concretes proportioned for desired porosities. Construction and Building Materials, 25 (2011), pp. 4181-4189.

[15] Yu, C., Wang, K., Liang, D.: Mechanical properties of pervious cement concrete, Cent. South Univ. (Springer), 19 (2013), pp. 3329–3334.

[16] Neithalath, N., Sumanasooriya, M.S., Deo, O.: Characterizing pore volume, sizes, and connectivity inpervious concretes for permeability prediction, Materials Characterization, 61 (2010), pp. 802-813.

[17] Cundall, P.A., Strack, O.D.L.: A discrete numerical model for granular assemblies, Geotechnique, 29 (1979), pp. 47-65.

[18] Itasca, Consulting, Group, Inc., PFC manual, 2008.

[19] Potyondya, D.O., Cundall P.A.: Abonded-particle model for rock, International Journal of Rock Mechanics & Mining Sciences, 41 (2004), pp. 1329-1364.

[20] Lian, C., Zhuge, Y., Beechan. S.: Numerical simulation of the mechanical behaviour of porous concrete, International journal for computer aided engineering and software, 28 (2011) 8, pp. 984-1002.

[21] Lian, C., Zhuge, Y., Beechan, S.: Modelling pervious concrete under compression loading - A discrete element approach, Advanced materials research, 168-170 (2011), pp. 1590-1600.