# Overview of meshfree modeling of the flowability of fresh self-compacting concrete for sustainable structures

*Kennedy C.* Onyelowe[1,2], *Denise-Penelope N.* Kontoni[2,3,*], *Michael E.* Onyia[4], *Atefeh* Soleymani[5], *Ahmed M.* Ebid[6], and *Hashem* Jahangir[7]

[1]Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria
[2]Department of Civil Engineering, School of Engineering, University of the Peloponnese, GR-26334 Patras, Greece
[3]School of Science and Technology, Hellenic Open University, GR-26335 Patras, Greece
[4]Department of Civil Engineering, Faculty of Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria
[5]Department of Civil Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[6]Department of Structural Engineering, Future University in Egypt, New Cairo, Egypt
[7]Department of Civil Engineering, University of Birjand, Birjand, Iran

**Abstract.** The flow of Bingham non-Newtonian incompressible fluids like concrete is associated with the large deformation of materials. The modeling and simulation of these fluids' flow behavior by using conventional numerical methods. suffer problem-formulation setbacks due to mesh distortion. In order to compensate for the mathematical inefficiencies encountered in the process, particle-based methods have evolved and been applied. Also, the use of some particle-based methods produces a stretch of unreliability due to the Eulerian algorithmic trail, which visits every particle edge allowing for revisiting vertices during its operation. This makes the model path cumbersome and time-consuming. Concrete flow is an important element of sustainable infrastructural development, and its understanding strengthens the efficiency of concrete handling and placement during construction activities. In this paper, a mesh-free method of modeling the flowability of self-compacting concrete (SCC) known as the smoothed particle hydrodynamics (SPH) has been reviewed. It derives its advantage from the Lagrangian algorithmic trail. This explores its merits and demerits in the concrete construction industry to propose the best practices for the passing ability, filling ability, and dynamic stability of the flowing fresh concrete (FFC)

## 1 Introduction

Concrete has been primarily used in the construction of buildings, roads, bridges, pipelines, etc. As sustainable concrete projects have proliferated, so have the requirements for concrete quality [1, 2]. A concentrated dispersion of solid particles in a viscous fluid called cementitious material concrete [3]. It is thought that cement paste, which is composed of cement granules spread in water, is not uniform [2]. Because the dimensions of the components of concrete vary from millimeter to millimeter, the fluid properties of concrete are difficult [4, 5]. That is important to describe the properties of fresh concrete since the casting, consolidation, and forming processes may affect the hardened concrete's long-term strength. For instance, a number of factors may shorten the lifespan of concrete structures because of their compactness. These problems are a result of the structure's internal aggregate segregation and inadequate formwork filling. Therefore, it is essential to create numerical methods for forecasting the flow, the coarse particle distribution, and the capabilities of filling and passing to save resources and efforts [6].

The term rheology is employed to explain how matter deforms and flows in the presence of external loads and different rates of shear. In 1920, Bingham proposed the "rheology" term for the first time. The fresh concrete's flowability can be understood more easily by using the flow curves which are connected to yield stress, plastic viscosity, and shear rates. This concrete's fresh state features can be evaluated statistically and objectively using rheology parameters. Rheology is related to the flowability, compatibility, and stability of concrete production as well as inter-particle friction, cohesion, and viscosity (bleeding, segregation) [7, 8].

The rheological properties of fresh concrete are complex and diverse. For the building material's quality to be guaranteed, freshly laid concrete must be suitably useable [1]. Tanigawa [9] published the concept and method for determining the workability of concrete using numerical flow simulation in 1988. To move and cast fresh concrete into formwork without excessive segregation, the concrete should be useable [10]. The types of workability include flowability, filling capacity, passage capacity, pumpability, segregation resistance, and others. The two main problems are flowability and segregation resistance. Flowability affects productivity levels, and segregation resistance affects the hardened

*Corresponding author: kontoni@uop.gr

concrete's performance, including static and dynamic segregation resistance [11]. The standard concrete's flowability is frequently affected by a wide range of parameters, such as cement content and fineness, the coarse-to-fine ratio of particles, the ratio of water to cement, and the use of chemical admixtures [12].

The most commonly used methods to determine if the concrete is fresh are the L-box, V-funnel, flow or spread table, and slump tests [13]. The flow test with the flow table equipment seems to be another beneficial method for evaluating mortar quality on a lab scale [14]. That's because a slight modification in the method of execution could result in different results. Such experiments were discovered to be extremely sensitive [15, 16]. Mechanisms must be devised to quantify fresh concrete's physical characteristics.

In the past, new qualities have also been connected to parameters using a variety of empirical evidence. To model the flow of concrete, rheometer testing and several numerical models were provided. Since they offer physical quantities linked with the basic flow behavior of concrete, rheometers are thought to be superior. These measurements can accurately estimate the fresh concrete's flowability to be used in different applications, such as SCC and 3D printing. While concrete modeling yields more accurate findings after being fully constructed, it is utilized to predict more correctly the flow characteristics from its composition [8]. It was discovered that the models built on the composition utilized in the past had restrictions due to one or more factors. Due to the measuring tools' limits, some were discovered to be loosely connected to the rheological measurements. Some simply provide one factor, which is insufficient to forecast how fresh concrete will flow. In certain models, the impacts of aggregate characteristics, including surface roughness, size, and form, were not taken into account [15].

In this research paper, the deployment of the SPH in the modeling of the flow behavior of fresh SCC has been reviewed and its superior qualities reported.

## 2 General Review on Flowability of Self-Compacting Concrete

Basis of previous studies [17, 18] has demonstrated that the fineness, content, and type of aggregates have an impact on concrete's flowability in addition to the use of superplasticizers. To create highly flowable, however cohesive cement-based products, Khayat [19] studied various forms of viscosity-enhancing admixtures. Additionally, limestone powder (LP)'s physical and chemical effects can effectively enhance cement-based composites' new features. In their own research, Cortes et al. [20] summarized the mechanical and rheological conduct of variously shaped sand particles and concluded that using angular-shaped fine aggregates rather than spherical aggregates of similar grading would result in a greater amount of paste being needed to achieve the desired flowability and strength. Waarde et al. [21] employed the Bingham model in a two-dimensional model based on the V-funnel test of fresh concrete. They ignored adjusting the slipping resistance on the borders of the concrete's flow. The obtained numerical results do not closely reflect the experimental data. The results showed that, compared to the concrete mixture with water-to-cement ratios of 0.43 and 0.45, the concrete mixture with a water-to-cement ratio of 0.41 caused higher differences between the experimental and numerical outcomes.

In order to construct concrete, Hwang et al. [22] substituted fast-cooling spherical steel slag for the natural aggregates. As the substitution rate increased, the concrete's workability, flexural strength, and compressive strength all improved. The impacts of five varieties of sand on the flowability of mortar were examined by Estephane et al. [17]. They discovered that regular sand with a sub-rounded form needs less water to obtain the desired flowability value. Nazar et al. [8] utilized the viscosity equations of dense suspensions and flow curves to conduct a rigorous evaluation of suitable rheological models. They provided a description of the cementitious material's flowability as a whole. Following the significant parameters mentioned in the equation of theory, their research concentrated on the effects of temperature, cement hydration, mixing methods and sequence, air entrainment, vibration, time, and pressure on rheology. The recycled spherical glass was utilized as aggregate to improve the flowability of concrete.

When the right carbon nanotubes (CNTs) dispersion method and mixing process were applied several authors claimed a modest improvement in the flowability of modified concrete [23]. Collins et al. [24] investigated how different w/c levels affected the initial properties of added carbon nanotubes to cement. The scientific report claims that increasing the w/c proportion will enhance the flowability of specimens. As a result, Estephane et al. [17] investigated the effects of carbon nanotube/cement mortar at different carbon nanotube loadings, from 0.1 percent to 0.5 percent, at varied water/binder proportions. At 0.4 percent water/binder proportion and 0.1 percent carbon nanotube loading, the specimen attained 240-millimeter flowability, which fell to 104 mm at 0.5% carbon nanotube concentration. Collins et al. and Ha, and Kang [24, 25] observed a comparable decrease in flowability with increased CNT concentration. Skripkiunas et al. [26] observed that adding 0.25 percent doses of carbon nanotubes to cement, by weight, caused the plastic's viscosity to rise by about 29.59 percent. The flowability of cement composites, including carbon nanotubes, is affected by the w/c proportion, the inclusion of fine fillers such as micro silica, fly ash (FA), sonication, and processing of the carbon nanotubes, their quantity, and their types. Aydın et al. [27] scientific study examined the effects of 2% weight replacement of cement by nano-silica (NS) and 40% weight replacement of cement by FA at a fixed w/c proportion (0.4) and carbon nanotube content (0.08 percent) The results of the study show that the addition of nano-silica to a concrete matrix devoid of carbon nanotubes and FA reduced fluidity by 29.25 percent, most likely as a consequence of the higher water requirements that the NS caused. The composite's flowability specimen significantly improved after FA was added compared to the specimen generated with nano-silica and carbon nanotubes, even though it was inferior to the control specimen's flow, without FA, carbon nanotubes, and nano-silica. The literature review indicates that FA regulates concrete fluidity irrespective of the presence of nano-silica and Carbon nanotubes, whereas the addition of these components increases concrete viscosity. The FA which was mixed with nano-silica and carbon nanotubes did not significantly increase the concrete's flowability.

## 3 Modeling Flowability of Fresh Concrete by Smoothed Particle Hydrodynamics

### 3.1 Preamble

Roussel et al. [5] summarized current computer models of freshly poured concrete. The Bingham model, which is commonly conceived of as a viscous fluid with yield strength, has been used to investigate the fresh concrete's constitutive law in the bulk of flow simulations published in prior works [5, 6, 28]. According to the Bingham model, the shear stress (τ) is a linear function of the shear strain rate ($\tau = \tau_0 + \eta_b\gamma$), where the yield stress ($\tau_0$) and the plastic viscosity ($\eta_b$) are fixed. The fresh concrete, having characteristics of both granular and fluid, is a viscous granular material, as opposed to being merely a viscous fluid [29]. Without a doubt, the particle interlocking and inter-particle friction in freshly formed concrete influence its flow properties and dependence on vertical loads. The Bingham model can be approximately used with high-fluidity concrete because it has pretty evident fluid characteristics, but it is problematic for regular concrete. To explain the characteristics of fresh concrete, such as time, nonlinear and pressure-dependent features, the viscous granular materials (VGM) framework was suggested [29]. Scientists have developed a unique numerical approach using the SPH and the VGM model [30]. This numerical method allowed for an accurate simulation of the L-box flow [31]. It is found that, at the minimum level of fluidity in the freshly mixed cementitious materials, the numerical results obtained from the VGM model may have higher precision in comparison to the Bingham model.

The continuum of the fluid is discretized into particles in the particle-based numerical method, referred to as smoothed particle hydrodynamics (SPH) [29]. The particles, α and β presented in the general formulation framework (Fig. 1), which have material qualities, serve as interpolating points. It can be roughly estimated by an integral interpolation for any field function *f(x)*

$$f(x) \approx \int f(x')\, W(|x - x'|, h)\, dx' \qquad (1)$$

In which,$h$ is the smoothing length and $W$ is a kernel function. Three requirements must be met by the kernel function $W$: the normalization, the compact condition, and the delta function characteristic. The number of kernel functions is enormous [32]. Here, the well-known cubic spine function was employed in this work.

$$W(q,h) = a_d \begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 \;, & 0 \le q < 1 \\ \frac{1}{4}(2-q)^3 \;, & 1 \le q < 2 \\ 0 \;, & q \ge 2 \end{cases} \qquad (2)$$

wherein $r$ is the distance between two particles and $q = r/h$. [33].

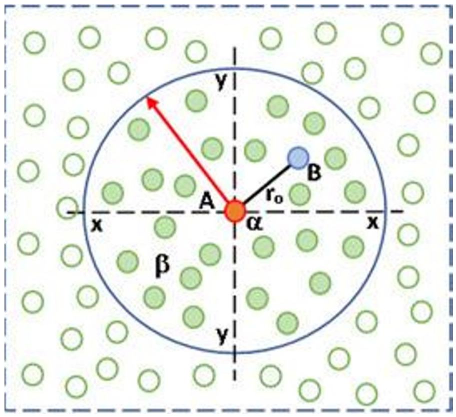


**Fig. 1.** General formulation framework of the SPH.

### 3.2 Literature Reviews on SPH SCC Flowability Modelling

Using the 2-D SPH, Lashkarbolouk et al. [34] proposed a model of the V-funnel test for SCC. Due to the 2-D SPH and the homogeneous fluid hypothesis, the results obtained from numerical analyses were less precise than the analytical outcomes. Nevertheless, these studies do not take into account the boundary limitation on the flow of fresh concrete. Deeb et al. [35]utilized smoothed particle hydrodynamics (SPH) to model the SCC's flow without or with steel fibers in the L-box test to assess the orientation and distribution of steel fibers.

In the research of Dhaheer et al. [36], a wide range of SCC mixtures with 28-day cube compression strengths ranging from 30 to 80 megapascals have been arranged in the science department. The J-ring test time t500J and the diameter of the flow spread for each mixture have been documented. The entire research was again repeated, lasting from the moment the cone was elevated until the mix stopped pouring. To obtain a combination of the continuity and Lagrangian momentum equations with the necessary Bingham-type constitutive model, the incompressible mesh-less smoothed particle hydrodynamics method was used to simulate the flow. The numerical simulation's goal was to examine how well the smoothed particle hydrodynamics methodology could forecast the flow of SCC mixtures via reinforcement bar gaps. The dispersion of huge coarse particles in the mixtures has been estimated and evaluated in various sections of the flow sheet to confirm the uniform flow behavior of the mixture. In a similar behavior in the experimental J-ring test, all modeled mixtures are found to satisfy the passage ability condition without blockage for t500J, aggregate homogeneity and the flow spread.

To model the V-funnel flow of SCC, Alyhya et al. [28] developed two-dimensional and three-dimensional smoothed particle hydrodynamics algorithms. They verified that the outflow time numerical simulation results obtained using the 3-dimensional smoothed particle hydrodynamics approach were remarkably consistent with the findings. The experimental data was longer than the outflow time obtained using the two-dimensional smoothed particle hydrodynamics approach. The 3-dimensional smoothed particle hydrodynamics and the Bingham model were utilized by AL-Rubaye et al. [6] to model the flow characteristics of SCC in the L-box test. The suggested method is extremely suited for SCC, as seen by the satisfactory correlation between actual L-box flow and numerical flow simulation.

In the research conducted by Cao et al. [33], smoothed particle hydrodynamics was used to investigate the opening flow behavior of fresh concrete. To handle the flow's boundary constraint during openings, they suggested a boundary restraint stress model, which made it clear that the normal stress acting on freshly laid concrete's shear plane grows throughout the opening flow. The model's parameters were developed by analyzing the theoretical and experimental results of the V-funnel flow test. The fresh concrete flow was then simulated using an L-shaped box made of steel bars. The results of numerical analyses demonstrated that when the fresh concrete has higher median particle contact and average particle friction angle, or the opening is narrow, the restriction of the opening's boundary significantly influences the flow behavior.

The impact of coarse particles on SCC was examined in Tran-Duc et al. study [37] by taking into account its pipe flow. A two-phase smoothed particle hydrodynamics model was utilized to model SCC as the suspension of coarse aggregates in cement mortar. Every coarse aggregate was characterized by a set of solid smoothed particle hydrodynamics particles that operate as a rigid body. As a yield-stress fluid, the cement mortar was described by fluid-smoothed particle hydrodynamics particles. According to the simulation study, more coarse aggregates—up to 24% in the circumstances under investigation—flow at a greater rate at the same volume fractions.

Using a 3D meshless smoothed particle hydrodynamics computational approach, in order to model the flow, a non-Newtonian Bingham fluid constitutive model was used for the self-compacting fiber-reinforced concrete (SCFRC) mixture. This numerical simulation by Mimoun and Kulasegaram [38] was designed to test the efficacy of the smoothed particle hydrodynamics methodology in forecasting the flow and passing ability of SCFRC mixtures through gaps in reinforcing bars. The orientation and the distribution of steel fibers in the mixtures of concrete have been modeled and checked with findings from laboratory studies to ensure that the concrete mixtures flow uniformly [39-40]. The simulated flow behavior of the SCFRC was found to compare favorably with the outcomes of the laboratory testing.

As stated earlier, the modeling of the studied concrete, which is a fluid concrete, owes its fluidity to the plasticizers, superplasticizers, high-range water absorbers (HRWA), viscosity modifying agents (VMA), etc. [41-43]. Research has shown that these additives and admixtures are environmentally responsible materials that reduce the carbon footprint of concrete [41-46]. It has been proven that these environmentally responsible materials improve the rheology of fresh concrete and the mechanical properties of the hardened concrete [45-46]. Furthermore, Thanha et al. [47] and Yu et al. [48] used engineered cementitious composite (ECC) and steel fiber considered environmentally friendly, respectively to model the flow of SCC using SPH. A few more research works have also applied environmentally conscious materials in various numerical applications to model SCC flow [49-55].

So, the numerical modeling of the concrete (SCC) produced with these eco-friendly materials takes into consideration, the influence of the materials on the stresses and flowability for sustainable engineering design and construction [42].

## 4 Conclusions

The superiority of the smoothed particle hydrodynamics (SPH) in modeling the flow behavior of concrete as an elastoplastic deformation problem has been extensively studied based on available literature.

The subject of flowability is a rheological characteristic of the self-compacting concrete (SCC), which was developed as a 21st-century concrete material innovation to overcome the difficulty of concrete handling, placement, workability, dynamic stability, and settlement especially in heavily reinforced structural members.

Over the years, this phenomenon has been studied using the Orimet flow, L-box flow, V-funnel flow, Cone flow, etc.

Analytical models have been used to study the physics behind the flow in SCC with results not too sufficient to deal with advanced cases.

Numerical models have also been deployed to take of the lapses of the analytical solutions but due to their Eulerian solution interface, their ability to deal with large deformations and mesh distortions is limited.

This review study has been able to explore the many possibilities of using the SPH in solving all the SCC flow models with ease and mathematical consistency due to its particle-based solution interface and its Lagrangian algorithmic system.

## References

1. Z. Xu, Z. Li, Cem. Concr. Compos. **123**, 104150 (2021)
2. K.C. Onyelowe, D.-P.N. Kontoni, A.M. Ebid, *3rd International Conference on Environmental Design, ICED-2022; IOP Conf. Series: Earth and Environmental Science* **1123**, 1-9 (012044) (2022)
3. K.C. Onyelowe, D.-P.N. Kontoni, A.M. Ebid, *3rd International Conference on Environmental Design, ICED-2022; IOP Conf. Series: Earth and Environmental Science* **1123**, 1-8 (012065) (2022)

4. D. Jiao, Shi C., Q.Yuan, X. An, Y. Liu, H. Li. Cem. Concr. Compos., **83**, 146–159 (2017)
5. N. Roussel, M.R. Geiker, F. Dufour, L.N. Thrane, P. Szabo, Cem. Concr. Compos., **37**(9), 1298–1307 (2007)
6. Al-Rubaye M., Kulasegaram S., Karihaloo B.L. Mag. Concr. Res., **69**(12), 618–628 (2017)
7. P.F.G. Banfill, *Rheology of Fresh Cement and Concrete* (CRC Press, 1990)
8. S. Nazar, J. Yang, B.S. Thomas, I. Azim, S.K. Ur Rehman, J. Clean. Prod., **272**, 122701 (2020)
9. Y. Tanigawa, H. Mori, Cement Concrete, **501**, 11–20 (1988)
10. K.C. Onyelowe, A.M. Ebid, A. Riofrio, H. Baykara, A. Soleymani, H.A. Mahdi, H. Jahangir, K. Ibe, Sustainability, **14**(15), 9573 (2022)
11. L. Shen, L. Struble D., Lange, *Proceedings of the 2nd North American Conference on The Design and Use of SCC, (SCC2005),* (2005)
12. S.K. Adhikary, Ž. Rudžionis, R. Rajapriya Sustainability, **12(20)**, 8362 (2020)
13. H. Kim, T. Koh, S. Pyo, Constr. Build. Mater., **123**, 153–160 (2016)
14. ASTM 230/C230M. *Standard specification for flow table for use in test of hydraulic cement* (2008)
15. K.C. Onyelowe, D.-P.N. Kontoni, A.M. Ebid, F. Dabbaghi, A. Soleymani, H. Jahangir, M.L. Nehdi Buildings, **12(7),** 948 (2022)
16. K.C. Onyelowe, A.M. Ebid., H.A. Mahdi, A. Soleymani, J. Jayabalan, H. Jahangir, P. Samui, R.P.Singh, Cogent. Eng., **9(1)**, 2122156 (2022)
17. P. Estephane, E.J. Garboczi, J.W. Bullard, O.H. Wallevik, Cem. Concr..Compos., **97**, 125–142 (2019)
18. S. Roy, T. Miura, H. Nakamura, Y. Yamamoto, Constr. Build. Mater. **231**, 117153 (2020)
19. K.H. Khayat, Cem. Concr. Compos. **20(2–3)**, 171–188 (1998)
20. D.D. Cortes, H.-K. Kim, A.M. Palomino, J.C. Santamarina, Cem. Concr. Compos. **38(10),** 1142–1147 (2008)
21. F.Waarde, E.A.B. Koenders, J.A.L. a Nijeholt, J.C. Walraven In*: V. B. de G Schutter (Ed.), Self compacting concrete – SCC,* 417–422 (RILEM publications SARL, 2007)
22. E.-H. Hwang, J.-M. Kim, J.H. Yeon, J. Appl. Polym. Sci. **129(5),** 2905–2912 (2013)
23. A.J.N. MacLeod, A. Fehervari, W.P. Gates, E.O. Garcez, L.P. Aldridge, F. Collins, Constr. Build. Mater. **247**, 118524 (2020)
24. F.Collins, J. Lambert, W.H., Duan, Cem. Concr. Compos. **34(2),** 201–207 (2012)
25. S.-J. Ha, S.-T. Kang, J. Korea Concr. Inst. **28**, 67–74 (2016)
26. G.Skripkiunas, E. Karpova, I. Barauskas J., Bendoraitiene, G. Yakovlev, Adv. Mater. Sci. Eng. **2018**, 8963542 (2018)
27. A.C.Aydın, V.J. Nasl, T. Kotan, J. Build. Eng. **20**, 467–475 (2018)
28. W.S. Alyhya, S. Kulasegaram, B.L. Karihaloo, Cem. Concr. Compos., **100**, 47–59 (2017)
29. Liu G.-R., Liu M.B. *Smoothed particle hydrodynamics: a meshfree particle method*. World Scientific (2003)
30. K.C. Onyelowe, E.R. Sujatha, F.I. Aneke, A.M. Ebid, Cogent. Eng., **9**(1), 2122158 (2022)
31. G. Cao, Z. Li, Cem. Concr. Compos., **100**, 263–274 (2017)
32. F.Chevoir, F. Gaulard, N. Roussel, Europhysics Letters (EPL) **79**(1), 14001 (2007)
33. Cao G., Li Z., Xu Z. Constr. Build. Mater. **198**, 379–389 (2019)
34. H. Lashkarbolouk, A.M. Halabian, M.R. Chamani Mater. Struct. **47(10)**, 1729–1743 (2014)
35. R. Deeb, S. Kulasegaram, B.L. Karihaloo Comput. Part. Mech. **1(4)**, 391–408 (2014)
36. M.S. Abo Dhaheer, S. Kulasegaram, B.L. Karihaloo, Cem. Concr. Compos. **89**, 27–34 (2016)
37. T. Tran-Duc, T. Ho, N. Thamwattana, Int. J. Mech. Sci. **190**, 106046 (2021)
38. A.Mimoun, S. Kulasegaram, In: *Computational Modelling of Concrete and Concrete Structures*, 162–167, (CRC Press , 2022)
39. K.C. Onyelowe, D.-P.N. Kontoni, Int. J. Low-Carbon Technol. **18**, 530–541 (2023)
40. A.M. Ebid, K.C. Onyelowe, D.-P.N. Kontoni, A.Q. Gallardo, S. Hanandeh, Int. J. Low-Carbon Technol. **18**, 404–411 (2023)
41. K.C. Onyelowe, A.M. Ebid., Asian J. Civ. Eng. (2023)
42. K.C. Onyelowe, D.-P.N. Kontoni, S.R.M. Pilla, S. Hanandeh, A.M. Ebid, M. Razzaghian Ghadikolaee, L.U. Stephen, Asian J Civ Eng. (2023)
43. K.C. Onyelowe, A.M. Ebid, M.R. Ghadikolaee Asian, J Civ Eng. (2023)
44. K.C. Onyelowe, A.M. Ebid, S. Hanandeh, Asian J Civ Eng. (2023) https://doi.org/10.1007/s42107-023-00832-w
45. K.C. Onyelowe, A.M. Ebid, S. Hanandeh, Asian J Civ Eng. (2023) https://doi.org/10.1007/s42107-023-00829-5
46. K.C. Onyelowe, A.M. Ebid, S. Hanandeh, A. A.B., I.C. Moghal Onuoha, I.I. Obianyo, O.A. Ubachukwu, Asian. J. Civ. Eng. (2023)
47. H.T. Thanha, J. Lia, Y.X. Zhangb, *Advances in Engineered Cementitious Composite: Materials, Structures, and Numerical Modeling*, Chapter 10, 321-336 (Elsevier, UK, 2022)
48. R. Yu, L.L. Xu, K.K. Li, Y.Leng, Z.Y.Wang, J. Build. Eng. **59**, 105084 (2022)

49. Z. Xu, Z. Li, F. Jiang, Cem. Concr. Compos., **152**, 106679 (2022)
50. J. Reinold, G. Meschke, Comput. Mech. **69**, 891–910 (2022)
51. X. Zhou, Y. Xie, G. Long, X. Zeng, J. Li, F. Wang, Powder Technol., **416**, 118218 (2023)
52. X. Liu, X. Xie, L. Zhang, N. Lam, Int. J. Comput. Methods, 2241002 (2023)
53. R. Sassi, A. Jelidi, *Mag. Concr. Res.* (2023)
54. Y.K. Gujjala, H.M. Kim, D.W. Ryu, Arch. Comput. Methods Eng. **30(3)**, 1601–1622 (2023)
55. T. Tavangar, *Doctoral dissertation*, Université de Sherbrooke (2023)