A brief review on the fabrication and mechanical behavior of functionally graded concrete materials

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Abstract. Functionally graded concrete materials (FGCs) are new concrete composites whose functions and properties change with the spatial position. In this paper, the research status on the fabrication and mechanical behavior of FGCs was briefly reviewed, and the next work is also summarized.

1. Introduction

With the rapid development of science and technology, the requirements of material properties in various fields are becoming higher and higher. In complex environment (e.g., outer space), single material is often unable to work normally. Composite materials, combining the advantages of each component, provide the possibility to fix this problem. However, in some extreme conditions (high temperature, extreme cold, high pressure, etc.), traditional composites (e.g., laminated materials and fiber-reinforced composite materials) are also hard to fully meet expectations; for example, under elevated temperature, the use of two kinds of materials with different thermal expansion coefficients will lead to residual stress on the interface, and this may cause delamination of the interface and local or overall damage of the structure. The development of conventional composites is greatly limited by the interfacial failure due to material mismatch. In order to solve this problem, it is necessary to design new composite materials, which have no obvious or even no interface and can cope with complex environment.

Among various modern composites, functionally graded materials (FGMs) are representatives. In the preparation of such materials, two or more different constitutes are properly mixed so that the tailored properties and functions continuously change in the spatial position to meet the service requirements. The concept of FGMs was first proposed by Japanese scholars in the 1980s[1]. They were originally used to tackle the failure problem of the thermal protection system outside the space shuttle from thermal stresses. With the continuous development of materials, mechanics and chemistry, etc., FGMs have been widely used in many fields, e.g., mechanical industry, bio-medicine and nuclear energy engineering[2].

On the other hand, concrete material has become one of the most important engineering materials in the field of civil engineering, and is most widely used in China. As early as 1997, China's annual output of cement has exceeded 400 million tons, ranking the first in the world[3]. In the long run, concrete will still be one of the dominant engineering materials. Concrete is widely used because of its advantages, e.g., good mold-ability, high strength and durability[3]. However, the defects of concrete are also obvious, e.g., big weight, poor crack resistance and more complex site construction[3]. In view of these disadvantages of traditional concrete, researchers have put forward many types of
modified concrete, e.g., lightweight concrete[4], high-strength concrete[5], fiber-reinforced concrete[6], self-compacting concrete[7] and roller compacted concrete[8]. In addition, impervious concrete, water-absorption concrete, anti-freezing concrete and heat-resistant concrete have also been proposed for different service conditions[3].

Traditional or modified concrete materials can generally meet limited requirements in normal working conditions, but in some special cases where higher demands are needed (e.g., in marine splash zone, concrete should be resistant to chloride ion corrosion and also of satisfactory protection performance), they are difficult to work well. Considering that FGMs can make full use of the advantages of each component, functionally graded concrete materials (FGCs) came into being[9]. Compared with the traditional or modified concrete, the mechanical properties, impermeability, fire resistance and corrosion resistance of FGCs can be greatly improved. Good performance makes the application prospect of FGCs more broad, which also leads to plenty of research work from various aspects of FGCs, e.g., durability, protection performance, conductivity and application[9-12]. In this paper, we give a brief review on the fabrication and mechanical behavior of FGCs.

2. FGCs research

2.1 Fabrication of FGCs

Dias et al.[13] devised the preparation scheme, mix design, production machine creation and test evaluation method of fiber FGCs. Herrmann and Sobek[14] successfully prepared the functionally graded concrete (FGC) beam based on the principle of gradient spraying (see figure 1 and figure 2). In addition, some studies formed FGCs by layering[15-16]. Wang et al.[17] published a method for preparing FGC for green planting roof by coining process. The layered pouring process is disturbed by a lot of human factors, and the resulting gradation is not as good as spraying technology and coining process. This technology is generally limited to make small components in the laboratory, which is difficult to be used in the preparation of large members in practical engineering. In addition to the above three traditional ways, another new technique, i.e., 3D printing technology[18], which produces materials through layer by layer printing, and coincides with the characteristics of spatial continuity of FGCs, has also been applied in the manufacture of FGCs. For example, Lai et al.[19] made FGCs by 3D printing, which has the characteristics of accurate material preparation and high integrity. However, at present, the use of such technique in huge project is still questionable, due to the limitation of cost, site and equipment.

2.2 Experimental studies.

Shen et al.[20] conducted bending tests on several groups of fiber FGC beams with different volume fractions, and obtained the strength and toughness of the beams. Li and Xu[21] analyzed the bearing capacity and ductility of FGC beams composed of ultra-high toughness cement-based composite materials by four-point bending test. Also through four-point bending test, Zhang[22] utilized confining pressure model test to study the bearing capacity of shaft wall of FGCs. Herrmann and Haase[23] investigated the influence of gradient arrangement and reinforcement form on the flexural capacity of FGC beams. Xiao et al.[24] evaluated the bending resistance of FGC plates with different recycled coarse aggregate. Mastali et al.[15] executed drop weight and bullet impact tests on FGC plates with different volume fractions of fibers. Naghibdehi et al.[25] reported the
mechanical properties of FGC beams made of steel fiber and polypropylene fiber under cyclic load. Based on the results of four-point bending test, Wan[26] analyzed the failure mode, deflection, crack and surface concrete strain of FGC beam. Toader et al.[27] developed new FGCs using bionic technology, and analyzed the deformation capacity and energy absorption capacity of the new FGCs by quasi-static and dynamic compression tests. Pietras and Sadowski[28] proposed the functionally graded autoclaved concrete and assessed its mechanical behavior by three-point bending test, compact shear test and modified Brazilian test. In the work of Yuan et al.[29], the four-point bending test was conducted to investigate the effects of interface bonding condition, fiber mesh reinforcement and failure pattern on the flexural behavior of FGC beam. Through the compressive strength test, Miao et al.[30] determined the influence of multi-factors (e.g., water binder ratio, fly ash, silica powder and polycrylate emulsion) on compressive strength of polymer cement-based FGC.

2.2.2 Theoretical and numerical studies. Some scholars discussed the mechanical properties of FGCs by theoretical analysis or numerical simulation. In theoretical studies, the explicit or closed solutions are analytically derived on condition that the material graded functions are predefined. Zhang et al.[31] introduced the functional gradient into the thick wall lining, and obtained the elastic modulus of FGC lining by back analysis. Zhang et al.[32] established the solution model of internal force and deformation of FGC lining structure based on the existing design theory of metro lining structure. Due to the influence of material gradient form, load type and structure geometry, it is a difficult task to solve complex practical problems using analytical approach.

Being able to simulate more complex problems at low cost, numerical methods have been widely adopted in the study of mechanical behavior of FGCs, among which the representative method is the finite element method (FEM). In the FEM, the idea of layered model is often used to approximate the spatially change of material properties. In detail, in the modeling, FGCs are divided into a certain number of layers along the graded direction, and each layer is treated to be homogeneous (see figure 3). With this idea, Roesler et al.[33-34] used commercial FEM software ABAQUS to simulate the fracture behavior of FGC beams composed of fiber reinforced concrete. Evangelista et al.[35] carried out the numerical simulation of the crack resistance of FGCs with ABAQUS. Wang et al.[36] analyzed the shrinkage cracking and interface bond strength of FGC segment in the river crossing tunnel through the FEM commercial software ANSYS. Park et al.[37] investigated the fracture of fiber FGC beams by cohesive zone model in the platform of ABAQUS. Under the guidance of existing tests, Wan[26] further analyzed the cracking of FGC beam with ABAQUS. Gao et al.[38] inspected the influence of the heat on the mechanical properties of the bridge deck by ABAQUS. Through ANSYS, Li et al.[39] conducted in-depth study on deformation coordination characteristics of high rolling FGC gravity dam. Zhang et al.[40] used the FEM to analyze the thermal and post buckling performance of FGC plates. Strieder et al.[41] investigated the possible effect of FGCs distribution in mass concrete structures on crack reduction by FEM.

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Figure 3. N-layered finite element model of a simply supported FGC beam.

3. Concluding remarks
In this paper, we briefly reviewed the work related to the fabrication and mechanical behavior of FGCs. Although a lot of work has been carried out, due to the complexity of FGCs, there are still many issues
to be further explored, e.g.,
(1) The manufacture of larger-scale FGCs with higher efficiency, higher quality and higher applicability;
(2) The development of advanced test apparatus and systems to conveniently and accurately obtain different features of FGCs;
(3) The study of deformation and fracture behavior of FGCs under multi-field coupling (e.g., hygro-thermo-mechanical coupling);
(4) The development of more accurate and efficient numerical methods or models for the simulation of FGCs, especially from 3D viewpoint;
(5) The development of new FGCs through artificial intelligent techniques combined with experimental or analytical or numerical tools.

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References
[1] Koizumi, M. (1997) FGM activities in Japan. Compos. Pt. B-Eng., 28(1-2): 1-4.
[2] Cao, L.L., Pei, J.Z., Chen, J., et al. (2014) Research progress in thermal stress of FGM. Mater Rep, 28(23): 46-50+54. (in Chinese)
[3] Jiang, J.J. (2007) Advanced theory of concrete structures. CABP Publishing, Beijing. (in Chinese)
[4] Kurt, M., Gul, M.S., Gul, R., et al. (2016) The effect of pumice powder on the self-compactability of pumice aggregate lightweight concrete. Constr. Build. Mater., 103: 36-46.
[5] Sharmila, P., Dhinakaran, G. (2016) Compressive strength, porosity and sorptivity of ultra fine slag based high strength concrete. Constr. Build. Mater., 120: 48-53.
[6] Hao, Y.F., Hao, H., Chen, G. (2016) Experimental investigation of the behaviour of spiral steel fibre reinforced concrete beams subjected to drop-weight impact loads. Mater. Struct., 49(1-2): 353-370.
[7] Leung, H.Y., Kim, J., Nadeem, A., et al. (2016) Sorptivity of self-compacting concrete containing fly ash and silica fume. Constr. Build. Mater., 113: 369-375.
[8] Rao, S.K., Sravana, P., Rao, T.C. Investigating the effect of m-sand on abrasion resistance of roller compacted concrete containing GGBS. Constr. Build. Mater., 122: 191-201.
[9] Wen, X.D., Yu, L.F., Tu, J.L., et al. (2013) Analysis of protective performance of gradient structure concrete in marine splash zone. J. Cent. South Univ. (Sci. Technol.), 44(02): 792-798. (in Chinese)
[10] Lin J. Durability model experiment and life prediction of subway ultra-high toughness concrete functionally graded track plate. Master’s thesis, East China Jiaotong University, 2018. (in Chinese)
[11] Miao, F.S., Ma, H.L., Liu, N., et al. (2019) Influence of multi-factors on electric flux of polymer cement-based functionally gradient concrete. Journal of Shihezi University (Natural Science), 37(2): 176-182. (in Chinese)
[12] Kovaleva, D., Gericke, O., Kappe, J., et al. (2019) Rosenstei pavilion: Design and structural analysis of a functionally graded concrete shell. Structures, 18: 91-101.
[13] Dias, C.M.R., Savastano, H., John, V.M. (2010) Exploring the potential of functionally graded materials concept for the development of fiber cement. Constr. Build. Mater., 24(2): 140-146.
[14] Herrmann, M., Sobek, W. (2017) Functionally graded concrete: Numerical design methods and
experimental tests of mass-optimized structural components. Struct. Concr., 18(1): 54-66.

[15] Mastali, M., Naghibdehi, M.G., Naghipour, M., et al. (2015) Experimental assessment of functionally graded reinforced concrete (FGRC) slabs under drop weight and projectile impacts. Constr. Build. Mater., 95: 296-311.

[16] Liu, X.Z., Yan, M.P., Galobardes, I., et al. (2018) Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete. Constr. Build. Mater., 171: 793-801.

[17] Wang YB, Zheng Z, Q., Peng K, et al. Functionally graded concrete for green planting roof and its preparation method. Chinese Patent, CN109293299A, 2018. (in Chinese)

[18] Yung, W.K.C., Sun, B., Meng, Z.G., et al. (2016) Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete. Constr. Build. Mater., 171: 793-801.

[19] Lai JZ, Zheng XB, Wang Q, et al. Functional gradient and density gradient concrete materials for 3D printing and their preparation methods. Chinese Patent, CN107555895A, 2017. (in Chinese)

[20] Shen, B., Hubler, M., Paulino, G.H., et al. (2006) Manufacturing and mechanical testing of a new functionally graded fiber reinforced cement composite. In: Multiscale and Functionally Graded Materials. Oahu, Hawaii. pp. 519-524.

[21] Li, Q.H., Xu, S.L. (2009) Experimental investigation and analysis on flexural performance of functionally graded composite beam crack-controlled by ultrahigh toughness cementitious composites. Sci. China. Ser. E., 52(6): 1648-1664.

[22] Zhang N. Study on bearing behavior of functionally graded concrete shaft lining. Doctoral thesis, North China Electric Power University, 2012. (in Chinese)

[23] Herrmann, M., Haase, W. (2013) Load bearing behaviour of functionally graded concrete components under flexural and shear stress. Beton- Stahlbetonbau, 108(6): 382-394.

[24] Xiao, J.Z., Sun, C., Jiang, X.H. (2015) Flexural behaviour of recycled aggregate concrete graded slabs. Struct. Concr., 16(2): 249-261.

[25] Naghibdehi, M.G., Naghipour, M., Rabiee, M. (2015) Behaviour of functionally graded reinforced-concrete beams under cyclic loading. Gradev., 67(5): 427-439.

[26] Toader, N., Sobek, W., Nickel, K.G. (2017) Energy absorption in functionally graded concrete bioinspired by sea urchin spines. J. Bionic Eng., 14(2): 369-378.

[27] Pietras, D., Sadowski, T. (2019) A numerical model for description of mechanical behaviour of a functionally graded autoclaved aerated concrete created on the basis of experimental results for homogenous autoclaved aerated concretes with different porosities. Constr. Build. Mater., 204: 839-848.

[28] Yuan, H.Q., Li, H.Y., Cui, Z.Y., et al. (2019) The flexural behavior of unbounded concrete-ECC functional composite beam. J. Railw. Sci. Eng., 16(7): 1765-1773. (in Chinese)

[29] Miao, F.S., Li, L., Li, X. (2019) Influence of multi-factors on compressive strength of polymer cement-based functionally gradient concrete. Science Technology and Engineering, 19(25): 318-324. (in Chinese)

[30] Zhang, N., Lu, A.Z., Li, C.C., et al. (2017) Support performance of functionally graded concrete lining. Constr. Build. Mater., 147: 35-47.

[31] Zhang, T.T., Cui, Z.D., Wang, S.Y. (2019) Deformation properties of functionally graded lining in deeply buried subway tunnel. J. Tianjin Univ., 52(z1): 135-140. (in Chinese)

[32] Roesler, J., Paulino, G., Gaedicke, C., et al. (2007) Fracture behavior of functionally graded concrete materials for rigid pavements. Transp. Res. Record, (2037): 40-49.

[33] Roesler, J., Bordelon, A., Gaedicke, C., et al. (2006) Fracture behavior and properties of functionally graded fiber-reinforced concrete. In: Multiscale and Functionally Graded Materials. Oahu, Hawaii. pp. 513-518.

[34] Evangelista, F., Roesler, J., Paulino, G. (2009) Numerical simulations of fracture resistance of
functionally graded concrete materials. Transp. Res. Record, (2113): 122-131.

[36] Wang, X.G., Sheng, M.Q., Wang, R., et al. (2010) Shrinkage cracking of functionally gradient concrete segment used in river-crossing or sea-crossing tunnels. J. Yangtze. River. Sci. Res. Inst., 27(02): 54-59. (in Chinese)

[37] Park, K., Paulino, G.H., Roesler, J. (2010) Cohesive fracture model for functionally graded fiber reinforced concrete. Cem. Concr. Res., 40(6): 956-965.

[38] Gao, Y.L., Huang, L., Zhang, H.L. (2016) Study on anti-freezing functional design of phase change and temperature control composite bridge decks. Constr. Mater., 122: 714-720.

[39] Li, M.C., Shen, Y., Zhang, M.X., et al. (2018) Deformation coordination analysis of RCC gravity dams with functionally graded structures. J. Hydroelectr. Eng., 37(8): 94-102. (in Chinese)

[40] Zhang, H.Q., Zhang, Z., Wu, H.L., et al. (2018) Thermal buckling and postbuckling analysis of functionally graded concrete slabs with initial imperfections. Int. J. Struct. Stab. Dyn., 18(11): 1850140-19.

[41] Strieder, E., Hilber, R., Stierschneider, E., et al. (2018) FE-study on the effect of gradient concrete on early constraint and crack risk. Appl. Sci.-Basel, 8(2): 246.