UDC 666.973.2:666.97.031 **DOI 10.52928/2070-1683-2023-35-3-69-74**

SHOTCRETES AND MORTARS FOR 3D PRINTERS USING CHINESE INDUSTRIAL WASTE

A. YAGUBKIN[1], M. GUONA[2], prof. H. WANG[3]
([1], [2]Euphrosyne Polotskaya State University of Polotsk,
[3]Nanjing Tech University)
[1]ORCID https://orcid.org/0000-0003-4124-3634,
[2]ORCID https://orcid.org/0000-0003-3970-0509,
[3]ORCID https://orcid.org/0000-0001-7742-9583

Currently, ordinary Portland cement is the main cementing material for shotcrete in tunnels in my country. Part of the use of single-doped silica fume or fly ash, however, there are few cementitious materials that use double-doped or multi-doped mineral admixtures. Due to the single composition of the cementitious material, poor gradation, and low quality, the concrete has poor compactness, insufficient viscosity, and large rebound. The use of "multiple" mineral admixtures can better solve the problem of high rebound rate of shotcrete in tunnels. Among them, mineral admixtures include mineral powder, fly ash, silica fume and limestone powder. The cementitious material in concrete can be single-mixed, double-mixed or multi-mixed with mineral admixtures. In this way, the heat of hydration when the concrete sets and hardens can be reduced, reduce the cracking of concrete, improve the compactness and viscosity of concrete and reduce the rebound rate of concrete.

The aim of research: the overall idea and technical measures to solve the high rebound rate of shotcrete or 3D printer mix and the high amount of cementitious materials using Chinese industrial waste.

Scientific novelty of research: optimal compositions using Chinese industrial waste for wet shotcrete, optimal compositions using Chinese industrial waste for 3D construction printers, basic properties of wet shotcrete composites with using Chinese industrial waste, basic properties of 3D construction printer composites with using Chinese industrial waste.

Keywords: *wet, shotcrete, 3D construction printer mix, quality, control, composites, industrial waste, fly ash, organic aggregates.*

Introduction. With the development of the third industrial revolution [1; 2], science and technology play an increasingly important role in the process of promoting the development of productive forces, accelerating the transformation of science and technology into direct productive forces. While promoting the interpenetration among various disciplines, scientific research is also constantly developing in a comprehensive direction. 3D printing technology, which integrates mathematics, information, machinery, materials and chemistry [3], as a new type of rapid prototyping technology, has become one of the important technical symbols in the third industrial revolution. The development of manufacturing industry plays an important role. With the increasing improvement of 3D printing technology, the technology has been involved in various fields such as medical [4], automobile [5], construction [6; 7], military industry [8], etc., and has shown its huge productivity and unlimited potential. The emergence of 3D printing technology in the construction industry has demonstrated its superiority in terms of labor, construction period, and resource utilization [9; 10], making rapid manufacturing and industrialized production of future buildings possible, and even mass customization of personalized products. Construction, which will inevitably lead to a technological innovation in the construction industry [11–13]. As a new building construction technology [14], 3D architectural printing has innovated the traditional construction methods. While showing its huge production potential, it also inevitably puts forward new requirements for building materials.

The aim of research: The overall idea and technical measures to solve the high rebound rate of shotcrete or 3D printer mix and the high amount of cementitious materials using Chinese industrial waste. To achieve the aim, the following objectives were solved: make an overview of the experience of the Chinese construction industry in wet shotcrete and 3D constructions printers, to select the optimal composition and determine the main properties of shotcrete and mix for 3D construction printer using Chinese industrial waste, give recommendations on optimizing the composites and mixes with aggregates from Chinese industrial waste.

Main part. The equipment used in the spraying test is the TK500 wet spraying machine produced by Chengdu Yanfeng Technology Co., Ltd. Each mix ratio cuts and processes 6 sets of split tensile test piece (1d, 3d, 7d, 28d, 56d, 90d compressive strength), 1 One set of tensile test pieces (28d strength), one set of flexural test pieces (28d strength) and one set of electric flux test pieces (56d) are used to test the mechanical properties of shotcrete.

The steps to make the test piece are: (1) preparation and weighing of raw materials; (2) equipment trial run; (3) spray large board and bracket installation; (4) prepare materials according to the mix ratio; (5) spray large plates layer by layer; (6) cutting and processing of test pieces.

The larger the maximum size of gravel, the greater the rebound rate, and it is also prone to blockage. Therefore, 5～10 mm more than the maximum size of gravel is used. The unit water consumption is under the condition of satisfying spray construction. should be as small as possible. For general sprayed concrete, the slump is preferably14～16 cm. The water-cement ratio and unit cement volume should be specified in accordance. For medium-grade sprayed concrete, the unit cement volume is mostly about 450 kg/mm^3, and the water-cement ratio is mostly about 0,40～0,50. The addition rate and usage amount of mineral admixtures shall be set at appropriate values according to the performance required by shotcrete. Mineral admixtures include: silica fume, fly ash, limestone powder, blast furnace slag powder and straw, etc.

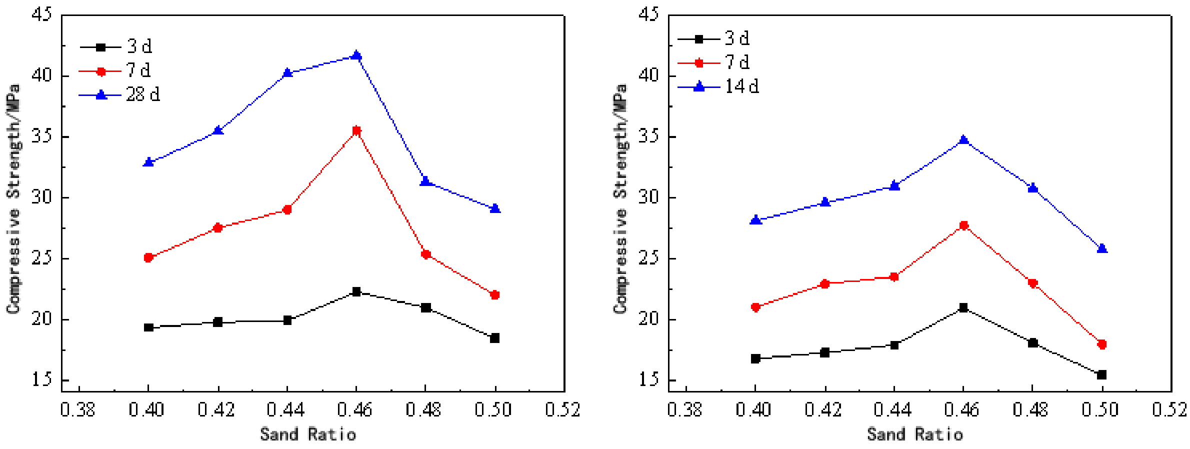
The water-binder ratio is 0,40 and 0,42. The amount of gelling material is 450 kg/m^3. Under the condition that the dosage of water reducing agent is 1%. Table 1 and figure 1 show the test results of concrete slump, expansion and compressive strength of different ages with different sand ratio formulas.

Table 1. – Compressive strength, slump and expansion of shotcrete with different sand ratios

Specimen №	water-binder ratio	Compressive strength (MPa)			Slump/mm	Expansion/mm
		3d	7d	28d		
A1	0,40	19,33	25,06	32,83	115	250
A2		19,76	27,51	35,44	120	265
A3		19,89	28,99	40,20	175	370
A4		22,27	35,52	41,69	185	410
A5		20,98	25,37	31,29	174	360
A6		18,43	21,98	29,07	165	355
B1	0,42	16,77	21,01	28,12	145	320
B2		17,28	22,92	29,57	155	340
B3		17,89	23,51	30,94	174	370
B4		20,94	27,72	34,71	198	425
B5		18,05	22,97	30,79	184	405
B6		15,41	17,96	25,75	155	345

From figure 1, *a*, it can be seen that when the sand rate is less than 0,46, the strength of each age of concrete increases continuously with the increase of the sand rate; when the sand rate is 0,46, the strength of each age reaches the maximum; when the sand rate is 0,50, the strength of concrete at each age reaches the minimum value. It can be seen from figure 1, *b* that when the water-binder ratio is 0,42, the strength changes of concrete at 3d, 7d, and 28d are basically the same as when the water-binder ratio is 0,40, when the sand ratio is 0,46, the strength reaches the maximum value.

Based on the above analysis, the test results show that when the water-binder ratio is 0,40, 0,42, and the sand rate is 0,46, the working performance of concrete and the compressive strength of each age are better than other sand rate conditions, so the optimal sand rate of wet shotcrete can be determined is 0,46.



a ***b***

***a* – W/B=0,40; *b* – W/B=0,42**

Figure 1. – Compressive strength of concrete at different ages with different sand ratios

It can be seen from figure 1 that the trend of concrete strength with the increase of sand ratio under the two conditions of water-binder ratio is basically the same, which shows that the influence of sand ratio on concrete strength basically shows a good regularity between 0,40 and 0,50. It is feasible to explore the optimal mix ratio of wet shotcrete by adjusting the sand rate. In order to fully consider the variability of raw materials on site and the strength factor of wet sprayed concrete, the actual concrete water-binder ratio is selected as 0,40.

The effect of the amount of cementitious material on the compressive strength of concrete. Under the conditions of sand rate 0,46 and water-binder ratio 0,40, the compressive strength of concrete at different ages with different amounts of cementitious materials is shown in table 2.

Table 2. – Compressive strength of concrete with different amount of cementitious material

Specimen №	Compressive strength (MPa)		
	3d	7d	28d
C1	22,27	35,52	41,69
C2	20,46	31,49	38,56
C3	16,03	22,92	28,39

It can be seen from table 2 that: when the sand ratio is 0,46 and the water-binder ratio is 0,40, the cementitious material dosage is 450 kg/m^3, and the strength of concrete at each age is the highest. Based on the comprehensive consideration of strength and cost, the optimal dosage of cementitious material is finally determined to be 450 kg/m^3, which not only ensures the strength of concrete, but also saves the amount of cementitious material and reduces the project cost.

The main characteristics of compositions for 3D printing with different straw fractions are shown in the table 3.

Table 3. – Compressive strength, density of compositions for 3D printing with different straw fractions

Specimen №	water-binder ratio	Compressive strength (MPa)			Density, (kg/m^3)	Note
		3d	7d	28d		
1	0,5	0,49	0,71	1,02	1138	Not suitable for load-bearing structures
2		0,77	1,07	1,53	1230	Not suitable for load-bearing structures
3		1,26	1,75	2,51	1195	Suitable for load-bearing structures

The prepared concrete must have an initial slump of about 200 mm, good workability, no segregation, and a 2 hour slump loss of less than 80 mm.

Through the slump test and adjusting the amount of water reducing agent to achieve the proper working performance of shotcrete, according to the test results of the aforementioned mix ratio scheme, the benchmark mix ratio is finally determined: the water-binder ratio is 0,40, the sand rate is 46%, and the water reducing agent is 0,8%. The amount of various materials is shown in table 4.

Table 4. – Amount of raw materials per cubic meter of concrete

Cementitious material (kg)	Mixed sand (kg)	Stone (kg)	Water (kg)	Superplasticizer (kg)	Density (kg/m^3)
450	791,2	928,8	180	4,0	2350

Conclusions and recommendations. Shotcrete or mix for 3D printer mainly sprays concrete mixed with a certain proportion of quick-setting agent on the rock surface with the help of a machine specially used for spraying with compressed air to strengthen the protection of the rock and realize the timely stress of the supporting structure. In the process of shotcrete construction, concrete pouring and vibration can be effectively combined into one process, reducing construction procedures and requiring no formwork. Therefore, this material is more suitable for narrow sites and projects that need to be stressed in time.

At present, concrete spraying methods are mainly divided into dry spraying and wet spraying. Traditional shotcrete mostly adopts dry spraying method, while wet spraying is better than dry spraying in terms of construction speed, construction quality and environmental protection. Therefore, wet spraying has gradually attracted more and more attention in these years. It has been applied and promoted in engineering.

In terms of construction speed, the spraying capacity of dry spraying process and dry spraying machinery and equipment is about 3 m^3/h, while that of wet spraying process and wet spraying machinery and equipment is 20 m^3/h. Therefore, the efficiency of wet spraying operation is significantly higher than that of dry spraying operation in the same time.

In terms of work efficiency, the overall construction speed of wet spraying is faster, especially in the construction of some ultra-long tunnels that require rapid excavation construction, and then it is necessary to spray concrete more quickly to strengthen the stability of the support as soon as possible, to prevent the occurrence of collapse accidents. Therefore, it is necessary to combine the wet spraying unit for concrete spraying, and the more efficient concrete spraying can greatly shorten the construction period and improve the safety of the operation.

In terms of construction quality, wet spraying is adopted. Since the concrete is produced in the mixing station, the mix ratio is stable, the overall compactness of the concrete is significantly higher than that of dry spraying, and the spraying quality is better.

In terms of construction environmental protection, the dust produced by the wet spray method is smaller, the spray rebound is less, and the physical impact on the workers will be lower. However, if the dry spray method is used, a large amount of dust will be generated during construction. Dust has greatly increased the pollution of the construction environment.

Technical measures to control the rebound rate of wet shotcrete:

1. Strictly control the quality of cement. When choosing cement materials, it is necessary to choose cement materials with less shrinkage as much as possible. The strength growth rate of materials with less shrinkage will be faster, and they can better react with the accelerator, effectively ensuring that the cement can be quickly sprayed after spraying. It reacts with the surface of the material to ensure the setting speed of the concrete and effectively reduce the amount of rebound.

2. Strictly control the quality of aggregate. When selecting sand, medium-coarse sand should be the main one, and the fineness modulus should be controlled between 2,8 and 3,2. Secondly, the mud content should be kept within 2,5%, and the moisture content should be controlled within 6%. The main reason for choosing coarse sand instead of fine sand is that too fine sand particle size will lead to an increase in the amount of cementitious materials and increase the shrinkage of concrete, resulting in excessive dust during construction, which will have a greater impact on the normal construction of workers. Large impact, and sand with too small particle size is not conducive to mixing with gravel, resulting in increased rebound. In the actual construction of sprayed concrete, it is necessary to select crushed stones with an appropriate particle size. Wear and tear of large machinery. However, if the particle size of the gravel is too small, it will affect the quality of shotcrete because of its insufficient structural strength. In actual construction, the sand and gravel in the mixing station will contain some moisture, and the distribution will be uneven. The moisture content test is accurate to ensure the stability of concrete workability.

3. Strictly control the quality of admixtures. During construction, accelerators with faster setting speed should be selected. Reduces rebound through faster setting. To prevent the condensation speed from being fast enough during actual construction, caused to fall off under the influence of gravity, moreover, when the condensation speed is fast enough, it can also ensure the timeliness and safety of construction.

4. Strictly control the mixing ratio. In the process of concrete spraying construction, in addition to strict screening of the quality of materials, the mix ratio between materials should also be strictly controlled.

5. Strictly control the construction process. Jet air pressure control. When spraying concrete, the length of the conveying pipe should be controlled within 15 m, and the wind pressure should be controlled at about 0,4 MPa. The wind pressure should be higher when spraying the vault, and the wind pressure should be lower when spraying the side wall. Reasonable control of the spraying distance and wind pressure can effectively control the rebound rate. Considering that the use of air ducts may cause waste of wind power, it is necessary to control the air source pressure in combination with the length of the tunnel and the sealing characteristics of the air ducts. In the actual construction process, the operators should strictly check the sealing performance of the mechanical air duct. If the sealing performance is high, the wind pressure can be appropriately reduced and controlled at around 0,3 MPa, so as to effectively control the site The amount of dust during actual construction should be controlled reasonably to rebound rate during concrete spraying.

6. Spray angle control. When spraying concrete, the condition of the sprayed structural surface should be checked first. If the sprayed structural surface itself is relatively flat, the nozzle should be controlled to be perpendicular to the structural surface during construction to prevent the problem of excessive rebound rate. If spraying is carried out in some relatively narrow places, the nozzle angle is controlled at about 70°, so that when the concrete is sprayed from the nozzle, it just falls on the top of the thicker concrete.

7. Spray distance control. In the process of spraying concrete, the grasp of the distance will greatly affect the rebound rate. When using the wet spraying method, the distance can be farther away, but if the distance is too long, the compaction degree will be insufficient and the strength will be weakened; if the distance is too small, the concrete will

fall off quickly due to the influence of wind pressure The problem. For this reason, when spraying concrete, the distance between the nozzle and the sprayed structural surface should be kept within 1 m to ensure a reasonable spraying distance [15].

8. Layered spray thickness control. In the process of spraying concrete, in order to prevent too much concrete attached to the structural surface due to excessive spraying of concrete, it will fall off and fall off under the influence of gravity. In the construction process, the layered spraying method can be selected, and the thickness can be reasonably controlled by spraying step by step, and the thickness of each layer should be reasonably controlled.

9. Spray interval time control. Since the spraying of concrete is not one-time, in actual operation, the operator needs to control the interval between each spraying. For example, after the first spraying, it is necessary to wait for a period of time to prevent the concrete from falling off due to the impact of wind pressure due to spraying again before the initial setting, resulting in an increase in the overall rebound rate. However, if the interval is too long, the new concrete cannot be well combined with the previous concrete because the previous concrete has already set, which increases the rebound rate of the concrete. Therefore, in the interval of spraying, it is necessary to ensure that the last sprayed concrete reaches the initial setting before spraying the next layer of concrete.

10. Improvement of steel mesh. The traditional lining of tunnels adopts reinforced mesh, which has a thick skeleton, high rigidity, and relatively large mesh size, which has little effect on reducing the rebound of shotcrete. In addition, the opening mesh is used, and it is difficult to connect each other during laying, which affects laying quality. In order to solve many problems of steel mesh, polyethylene polymer mesh can be used in shotcrete, as shown in figure 1, to replace the steel mesh in the traditional process, to make up for the limited performance of the steel mesh in the initial support of the tunnel, and the concrete in order to solve problems such as large rebound, the mesh is made of polyethylene polymer material, which makes it easy for workers to install through simple connections.

The general conclusions based on the results of the work are as follows:

1. Was made an overview of the experience of the Chinese construction industry in wet shotcrete and 3D constructions printers, including the experience of the Chinese construction industry in the implementation of the wet shotcrete, the experience of the Chinese construction industry in the implementation of the 3D constructions printers and the use of Chinese industrial waste in construction.

2. Were suggested methods for obtaining optimal compositions for wet shotcrete and mortars for 3D construction printers using Chinese industrial waste. Based on the proposed methods were substantiated optimal compositions using Chinese industrial waste for wet shotcrete and mortars for 3D construction printers.

3. Basic properties of wet shotcrete composites with using Chinese industrial waste have been researched. Basic properties of 3D construction printer composites with using Chinese industrial waste have been researched.

4. The results obtained are of great practical importance both for China and for the Republic of Belarus. Were given recommendations on optimizing the composites and mixes with aggregates from Chinese industrial waste.

REFERENCES

1. Li, Xiaoli, Ma, Jianxiong & Li, Ping. (2014). 3D Printing Technology and Application Trend. *Automatic Instrumentation*, *35*(1), 1–5.
2. Deng, Manqiu. (2014). The development prospect of the third industrial revolution 3D printing in China. *Digital Printing*, (2), 22–23.
3. Ding, Lieyun, Jie, Xu & Yawei, Qin. (2015). A review of research and application of architectural 3D printing digital construction technology. *Journal of Civil Engineering and Management*, *32*(3), 1–10.
4. Huang, Weidong, Lu, Xiaowei & Lin, Xin. (2011). Preparation of biomedical materials by laser forming Research status and development trend. *China Materials Progress*, (4), 1–10.
5. Liu, Guanchen. (2016). Analysis on the prospect of 3D printing technology in the future automobile industry. *Times Automobile*, (3), 33.
6. Wang, Qing. (2016). Application of 3D printing technology in construction engineering. *Architectural Science*, (34), 260.
7. Jiang, Lixin, Xiangxiang, Yi & Jie, Shao. (2013). The development of 3D printing technology and its application in the field of military industry. *Chinese Army to Civilian*, (12), 58–62.
8. Yang, Jianjiang & Xiang, Chen. (2015). 3D printing architectural technology and application trends. *Construction Technology*, *44*(10), 84–88.
9. Zhang, Hao & Yuchen, An. (2016). The application and prospect of 3D printing technology in the field of construction engineering. *Shanxi Architecture*, *42*(11), 17–18.
10. Zhang, Xiaoguang. (2014). Research on the development of architectural technology based on 3D printing era. *Henan Science and Technology*, (20), 162–163.
11. Hong, Yue. (2014). 3D printing architecture from theory to practice. *Green Building Materials*, (6), 58–62.
12. Yang, Jianjiang & Xiang, Chen. (2015). 3D printing architectural technology and application trends. *Construction Technology*, *44*(10), 84–88.
13. Wang, Wentao. (2014). The development trend of 3D printing manufacturing technology and its impact on my country's structural transformation. *Science and Technology Management Research*, (6), 22–25.
14. Wang, Cancai. (2012). Analysis of the development status of 3D printing. *Digital Technology*, (9), 38–39.
15. Chen, Lixin. (2020). Improvement measures for pipe plugging and high rebound rate in tunnel wet spraying manipulator construction. *Anhui Architecture*, *27*(12), 172.

Поступила 21.11.2023

ТОРКРЕТ-БЕТОНЫ И РАСТВОРЫ ДЛЯ 3D ПРИНТЕРОВ С ПРИМЕНЕНИЕМ ОТХОДОВ ПРОМЫШЛЕННОСТИ КИТАЯ

А. ЯГУБКИН[1], М. ГУОНА[2], проф. Х. ВАНГ[3]
([1], [2]Полоцкий государственный университет имени Евфросинии Полоцкой,
[3]Нанкинский технологический университет)

В настоящее время основным цементирующим материалом для торкрет-бетона в тоннелях является обычный портландцемент. Частично используется кварцевый песок или зола-унос, однако мало цементных материалов, в которых используются двухдобавочные или многодобавочные минеральные добавки. Из-за односоставности цементного материала, плохой градации и низкого качества бетон имеет плохую уплотняемость, недостаточную вязкость и большой отскок. Использование «многокомпонентных» минеральных добавок позволяет лучше решить проблему высокой скорости отскока торкрет-бетона в тоннелях. К минеральным добавкам относятся минеральный порошок, зола-унос, кремнеземный дым и известняковый порошок. Цементный материал в бетоне может быть однокомпонентным, двухкомпонентным или многокомпонентным с минеральными добавками. Это позволяет снизить теплоту гидратации при схватывании и твердении бетона, уменьшить растрескивание бетона, повысить компактность и вязкость бетона, уменьшить скорость отскока бетона.

Цель исследования: разработка общей идеи и технических мер по решению проблемы высокой скорости отскока торкрет-бетона или смеси для 3D принтера и большого количества цементирующих материалов с использованием отходов китайской промышленности.

Научная новизна исследования: оптимальные составы с использованием отходов китайской промышленности для мокрого торкретирования, оптимальные составы с использованием отходов китайской промышленности для 3D строительных принтеров, основные свойства композитов для мокрого торкретирования с использованием отходов китайской промышленности, основные свойства композитов для 3D строительных принтеров с использованием отходов китайской промышленности.

Ключевые слова: *мокрый, торкретирование, смесь для 3D строительного принтера, качество, контроль, композиты, промышленные отходы, зола-унос, органические заполнители.*