Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 4, No. 12, December, 2018

Effectiveness of Locally Available Superplasticizers on the Workability and Strength of Concrete

Ashfaque Ahmed Jhatial [a, b*], Samiullah Sohu [a, c], Muhammad Tahir Lakhiar [a], Jam Shahzaib [c], Ahsan Ali Buriro [c]

[a] *Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat 86400, Johor, Malaysia.*

[b] *Department of Civil Engineering, Mehran University of Engineering and Technology, Shaheed Zulfiqar Ali Bhutto Campus, Khairpur Mirs', Sindh, Pakistan.*

[c] *Department of Civil Engineering, Quaid-e-Awam University College of Engineering, Science and Technology, Larkano, Sindh, Pakistan.*

Received 17 August 2018; Accepted 25 November 2018

Abstract

Though Super Plasticizers (SP) are well-known chemical admixtures which are added into concrete to enhance the workability and achieve higher strength while reducing the water content. But the rapid increase in different SP in Pakistan has created confusion on the effectiveness of SP. This experimental study was carried out to study the effect of locally available SP on the workability and compressive strength of M15 grade concrete. Three different SP were utilized, with dosage ranging from 0.5% to 2.5% with an increment of 0.5%. The water-cement ratio remained constant at 0.5 for all samples. Based upon the results, all three SP increased the workability as well as strength of concrete. The optimum dosage was determined to be 1.5% to 2.00% for all three SPs used in this research work. BASF 561 was determined to be more effective, as it achieved the maximum workability as well as compressive and flexural strengths.

Keywords: Superplasticizers; Compressive Strength; Flexural Strength; Workability; Locally Available; Pakistan.

1. Introduction

Construction industry plays a significant role in uplifting the socio-economic development of any country [1]. Concrete is the most widely used building material in the construction industry [2] due to which it is considered as the backbone of any country's infrastructure [3], therefore, lack of such infrastructures becomes a barrier in the development of a country [4]. Concrete has vast applications ranging from the construction of foundations, retaining walls to bridges, dams and other structural members. Due to its availability and durability, concrete's popularity has been on the rise and has become the most widely used building material in the world [5]. But due to the rising demand for special qualities, conventional concrete has been lacking to satisfy this need. Therefore, researchers attempted to produce such special features and qualities with the use of chemical admixtures. In fact, the development and utilization of chemical admixtures in civil engineering applications has been one of the most important innovations of the 20th century, as these chemical admixtures not only help in reducing the cost of construction, enhancing or modifying the properties of hardened concrete but also ensuring quality during mixing, transporting, placing and curing [6, 7]. According to ASTM C494 [8], the chemical admixtures are classified into seven categories as shown in Table 1.

* Corresponding author: ashfaqueahmed@muetkhp.edu.pk

http://dx.doi.org/10.28991/cej-03091208

Table 1. Classification of admixtures according to ASTM C-494

S. No.	Type	Description
01.	Type A	Water-Reducing Admixtures
02.	Type B	Retarding Admixtures
03.	Type C	Accelerating Admixtures
04.	Type D	Water Reducing and Retarding Admixtures
05.	Type E	Water Reducing and Accelerating Admixtures
06.	Type F	Water Reducing, High Range Admixtures
07.	Type G	Water Reducing, High Range and Retarding Admixtures

Over the years increase in population and migration into urban areas as well as scarcity of landscape, a trend of vertical structures (high-rise buildings) has been growing. High-rise buildings require the use of concrete which can resist high compressive loads, thus giving rise to the development of high strength concrete, unfortunately the conventional concrete in common use does not achieve such high strength, without compromising the workability of concrete. Reducing the water content in concrete can increase the strength of concrete but on the other hand, its workability is severely affected making it hard to work with. To achieve high strength concrete without losing the workability, chemical admixture commonly known as superplasticizer (SP) is utilized [9]. The main benefits of utilization of SPs in concrete, also known as high range water reducers (HRWR), is increased workability, with low water content and normal workability the development of high strength concrete and development of strength and workability in a concrete mix with less content of cement. The utilization of SP is gaining ground in areas where there is limited water supply though certain workability is required to be achieved.

Pakistan is a developing country, the construction industry growth has been relatively slow, but with the "China-Pakistan Economic Corridor" initiative, a rapid development and construction of infrastructure is forecasted. At the same time, Pakistan is placing a water crisis, which is forecasted to increase over the years, therefore, it is imperative to focus on water conservation. Water places significant role in the manufacturing of concrete, therefore, reducing water usage in the concrete can potentially aid to conserve water. Therefore, SPs are a good handy solution to the water conservation. The utilization of SPs can reduce water content in concrete without adversely effecting the workability of concrete. Furthermore, new brands and types of SPs are pouring into the market for utilization. Each SP varies from one another, therefore, their effect on the behaviour and properties of concrete also vary.

Therefore, this experimental research aims to study the effect of various SPs which are locally available on the workability and strength of concrete. The objectives of this study are;

1. Effect of locally available SPs on the workability of M15 grade concrete.
2. Effect of locally available SPs on the compressive and flexural strength of M15 grade concrete.
3. Determination of optimum dosage for each SP in terms of workability, compressive and flexural strength of M15 grade concrete.

2. Literature Review

Concrete is an artificial composite material consisting of cement, aggregates and water [10]. Most of the important properties and characteristics of concrete depends upon the water content used in the concrete mix. With the reduction in water content, higher density can be achieved in cement paste, which enhances the quality of paste. This higher paste quality in concrete allows strength gain, increases resistance to weathering while lowering the permeability, reduces the volumetric change from drying and wetting, and reduce shrinkage cracking tendencies. High strength concrete can be developed without the utilization of admixtures, provided the water content is reduced and good workability is achieved. But with the reduction in water content, it is not easy to achieve such desirable workability. Therefore, SPs are utilized in concrete mix, which can reduce water content up to 30% without affecting the workability while provide significantly higher strength. SP is a type of chemical admixtures used in concrete, which compile to ASTM C494 Type F and G, and are capable of reducing the water content of a concrete mix by 15% to 30%, as compared to its predecessor, plasticizer, which was able to reduce water content by about 10 to 15%. The SP is not a relatively new innovation. But since its development in early 1960s, it's acceptance and utilization in construction industry has gradually increased.

A study was carried out on effect of SP on the behavior of normal concrete under different curing methods [11]. ASTM C494 type A and F, anionic melamine polycondensate, non-toxic SP was utilized. Four dosages of SP, ranging from 0.5%

to 2% was added into M20 grade concrete with a constant water-cement ratio of 0.48. The specimens were cured under four different curing conditions. Based upon the results, it was found that 0.5% dosage to be optimum in terms of enhancement of compressive strength. It was also observed that with the increase in SP dosage, the workability also increased.

The effect of addition of SP on the properties of normal strength concrete was studied [12]. The normal concrete was designed with characteristic strength of 30 MPa. Four dosages, i.e. 0.6%, 1.2%, 1.8% and 2.5% of SP was added in the concrete and the results were compared with concrete with no admixture. It was observed that, though the workability can be increased with the addition of SP, high dosages tend to impair the cohesiveness of concrete. Compressive strength was also noticed to have increased significantly with the addition of SP.

SP has been added in self-compacting concrete containing fly ash and its effect on the fresh and hardened properties was studied [13]. The dosage of SP was varied from 0.25% to 0.35% with an increment of 0.05% while the fly ash content remained constant at 10%. M20 grade concrete with 0.55 water-cement ratio was designed for this experiment. Based upon the results obtained, it was found that concrete containing fly ash and SP yielded good workability in addition to increase in compressive strength.

Due to such positive results in achieving higher workability and higher strength, the use of SPs has increased over the years. With gradual increase comes new types of SPs. An experimental work conducted by Shi et al. [14] to study the effects of such different types of SPs on the carbonation of concrete. Three different types polycarboxylic acid, naphthalene sulfonate and aliphatic based SPs were utilized, and it was determined that all three improved anti-carbonation performance of concrete. Though their magnitude varied with polycarboxylic acid-based SPgaining the highest. It was also observed that the effect of SPs is not entirely associated not with the pore structure, but the morphology of hydrated products also has some influence.

An experimental work was done by Mardani-Aghabaglou [15] to study the effect of polycarboxylate ether-based SPs on the fresh properties and the strength of self-compacting concrete. Four types of polycarboxylate ether SPs were utilized, which only differed in their molecular weight and different side chain density of carboxylic acid groups. It was observed that the different types of SPs affected the fresh properties as well as slightly influencing the compressive strength of self-compacting concrete.

A total of three different SPs, naphthalene, ether-based and ester-based polycarboxylate SPs were utilized in the study conducted by Yang [16] to determine the effect of type and dosage of SPs on the fluidity and strength properties of cement tailings backfills (CTB). The CTB mixes were proportioned varied sold content from 66% to 70%, while the SP dosage varied from 0% to 0.5% by mass of CTB. The results proved that not only the solid content had influence on the CTB performance, but the type and dosage of SP also played its role, with naphthalene-based polycarboxylate SPs demonstrated the best performance in terms of fluidity behavior of fresh CTB mixtures.

Nematollahi and Sanjayan [17] were conducted on the effect of commercially available SPs on the workability and strength of geopolymer paste. Three SPs, namely, naphthalene, melamine and modified polycarboxylate based SPs and two different activator combinations were used in this study. The SPs were added at 1% dosage by mass of fly ash. Based upon the results it was determined that the effect on the workability and strength of the fly ash geopolymer directly influenced by the type of SP as well as the activator. It was further observed that naphthalene-based SPs worked better when 8 M NaOH solution was used as the activator, while for the multi-compound activators the modified Polycarboxylate based SP proved to be effective.

3. Research Methodology

3.1. Materials

For this experimental work, M15 grade concrete (1:2:4) was prepared in which cement, fine and coarse aggregates was used. The water-cement ratio was kept constant at 0.5. To determine the change in performance of concrete, a chemical admixture (SP) was added.

Lucky Star cement, a product from cement industries of Pakistan was used in this study. This type-I cement complies strictly with PS 232:2015 and ASTM C150. Since almost three quarters of the volume of concrete is occupied by aggregates, they play an important role, therefore, all aggregates must be dust free as the dust may affect the bonding between the aggregates and the cement particles. The water absorption and specific gravity of the aggregates used is tabulated in Table 2. The fine aggregate used in this investigation was sieved through 4.75 mm sieve, while the coarse aggregates were crashed stones with a maximum size of 20 mm. The sieve analysis of coarse aggregates is shown in Table 3. In addition, aggregates should be cleaned before mixing to wash away the fine particles that stick on the surface of the aggregate.

Three different SPs which are locally available in Pakistan were used. The dosage ranged from 0% (control with no SP) to 2.5% with an increment of 0.5%. BASF Rheobuild 850 (SP A) was formulated from synthetic polymers specially designed to impart the rheoplastic qualities to concrete. The manufacturer dosage recommendation for normal concrete is 0.8% to 2.0%, while for high performance concrete, 1.5% to 3.0% is recommended. BASF Rheobuild 561 (SP B) is a naphthalene sulphonate based HRWR admixture which is added to improve the final strength of concrete by giving the concrete rheoplastic property. The dosage of SP B is suggested to be between 1.0% to 2.0% according to the manufacturer's recommendation. BASF Rheobuild 858 (SP C) is a HRWR admixture designed to produce high slump concrete with good workability. SP C considerably improves the properties of fresh and hardened concrete. The manufacturer dosage recommendation of SP C for normal concrete is 0.8% to 2.0%, while for high performance concrete, 1.5% to 2.5% is recommended. The properties of the three locally available SPs is shown in Table 4.

Table 2. Properties of Aggregates

Properties	Fine Aggregates	Coarse Aggregates
Water Absorption	0.7 %	0.45 %
Specific Gravity	2.60	2.75

Table 3. Sieve Analysis of Coarse Aggregates

Serial No.	Sieve Size (mm)	Weight Retained (g)	% of Weight Retained	Cumulative % of Weight Retained	% of Passing
01	12.5	0	0	0	100%
02	9.5	2435	81.16%	81.16%	18.84%
03	4.75	545	18.16%	99.32%	0.68%
04	2.36	10	0.33%	99.65%	0.35%
05	1.18	5	0.16%	99.81%	0.19%
06	Pan	5	0.16%	99.97%	0.03%

Table 4. Properties of Locally Available Superplasticizers

Properties	SP A	SP B	SP C
Colour	Dark Brown Liquid	Brown	Dark Brown
Specific Gravity	1.21	1.142	1.24
Chloride Content	Chloride Free	< 0.1	Chloride Free
Alkali Content	-	< 10	-
Standards	ASTM C-494 Type A, B, D, F and G.	ASTM C-494 Type G	ASTM C-494 Type A, B, D, F and G.

3.2. Experimental Work

The dry materials (cement, sand and coarse aggregates) were inserted into the concrete mixer and allowed to uniformly mix together. Afterwards specified water and respective SP and dosage were added and left to mix for few minutes. The slump test was conducted to determine the effect of SPs on the workability of concrete. Once the slump readings were recorded, the wet mix was poured into the cylindrical and beam moulds to be kept for 24 hours before demoulding and kept for water curing for 28 days. To determine the effect of SPs on the compressive strength of concrete, three cylindrical samples of 6×12 in were prepared for each dosage of SP, while three beams samples of $19.5 \times 4 \times 4$ in dimension were prepared to determine the flexural strength of concrete as shown in Figure 1.

Figure 1. Conducting the Flexural Test of Concrete

4. Results and Discussion

4.1. Workability

To study the effect of SPs on the workability, the slump test was conducted on fresh concrete. The workability was checked on fresh concrete in accordance to ASTM C143 [18]. The average slump results of concrete incorporating the three SPs is tabulated in Table 5.

Table 5. Average Slump of Locally Available Superplasticizers

% of SP	Average Slump (Inches)		
	SP A	SP B	SP C
0% (Control)		0	
0.5%	1.52	1.12	1.45
1%	4.5	2.4	2.68
1.5%	5.25	5.55	3.9
2%	5.9	6.05	4.8
2.5%	6.45	6.55	6.2

From Table 5, it is observed that a significant increase in slump occurred when 0.5% dosage of all SP was added. The highest slump for 0.5% dosage was recorded by SP A which was 1.52 inches, while SP B recorded 1.12 inches the lowest among the SPs. With the increase in dosage, the average slump also increased rapidly. The highest slump recorded was 6.55 inches when 2.5% dosage was used of SP B. This is significant increase as SP B showed a slow increase in slump compared to SP A and SP C.

It is evident that the synthetic polymer-based SP A achieved better workability than the other two local SPs. An average slump of 4.5 inches was achieved by SP A at 1% dosage while similar slump was achieved by SP B and SP C when higher dosage was used.

4.2. Mechanic Properties

The cylindrical and beam samples were tested in the Universal Testing Machine for the compressive and flexural strengths accordance to ASTM C39 / C39M – 18 [19] and ASTM C78 / C78M – 18 [20] respectively. Table 6 shows the average compressive strength obtained using SP A, SP B and SP C respectively, while Table 7 shows the average flexural strength of concrete incorporating three different SPs and varied dosages.

Table 6. Average Compressive Strength of Locally Available Superplasticizers

% of SP	SP A		SP B		SP C	
	Compressive Strength (MPa)	Diff. w.r.t. control (%)	Compressive Strength (MPa)	Diff. w.r.t. control (%)	Compressive Strength (MPa)	Diff. w.r.t. control (%)
0% (Control)	15.07	---	---	---	---	---
0.5%	19.41	+ 28.80 %	25.7	+ 70.54 %	22.44	+ 48.91 %
1%	20.98	+ 39.22 %	32.8	+ 117.65 %	24.88	+ 65.10 %
1.5%	22.70	+ 50.63 %	32.3	+ 114.33 %	30.57	+ 102.85 %
2%	27.14	+ 80.09 %	29.63	+ 96.62 %	29.32	+ 94.56 %
2.5%	20.7	+ 37.36 %	24.88	+ 65.10 %	16.65	+ 10.48 %

Table 7. Average Flexural Strength of Locally Available Superplasticizers

% of SP	SP A		SP B		SP C	
	Flexural Strength (MPa)	Diff. w.r.t. control (%)	Flexural Strength (MPa)	Diff. w.r.t. control (%)	Flexural Strength (MPa)	Diff. w.r.t. control (%)
0% (Control)	4.33	---	---	---	---	---
0.5%	4.81	+ 11.09 %	5.02	+ 15.94 %	5.63	+ 30.02 %
1%	6.30	+ 45.50 %	5.49	+ 26.79 %	6.65	+ 53.58 %
1.5%	6.50	+ 50.12 %	6.67	+ 54.04 %	7.01	+ 61.89 %
2%	8.26	+ 90.76 %	6.24	+ 44.11 %	6.00	+ 38.59 %

2.5%	5.78	+ 33.49 %	5.02	+ 15.94 %	4.73	+ 9.28 %

The normal concrete achieved its designed characteristic strength of 15 MPa. When SP A was added into concrete, 0.5% recorded 19.41 MPa which was 28.80% increase compared to the control sample. With further increase in dosage of SP A, the compressive strength also increased. The maximum compressive strength was recorded when 2.0% SP A was added, at which 80.09% increase gained in strength. Beyond this dosage the compressive strength of concrete started to drop, it recorded 20.7 MPa when 2.5% was added, which was still 37.36% higher than the control sample. It was also observed that for flexural strength, a slow increase in strength was seen for SP A compared to other SPs at 0.5% dosage. But with the gradual increase in the dosage, SP A gained higher strength such that the highest flexural strength was achieved at 2% by SP A which gave 90.76% increase than the control sample, thus suggesting that for SP A the optimum dosage is 2.0% at which the maximum strength can be achieve.

For SP B, 0.5% showed an impressive strength gain of 72.54% compared to the control sample. With further increase in dosage of SP B, the compressive strength also increased significantly, such that 1% of SP B achieved 32.8 MPa which was 117.65% higher than the control sample. This strength is significantly high, allowing normal concrete to be converted into high strength concrete. Further increase in dosage beyond 1% started to loss strength, though it was still significantly higher than the control sample, thus suggesting that for SP B the optimum dosage is 1%. Similar trend was noticed for the flexural in which the maximum flexural strength was observed at 1.5% dosage, gaining 54.04% increase compared to control sample. Corelated with the average slump, it is suggested that 1.5% dosage of SP B will achieve significant strength while giving better workability.

For the SP C, the addition of 0.5% the compressive strength increased to 22.44 MPa which was 48.91% higher than the sample without any SP added. The compressive strength increased with the dosage of SP C also increased such that with the addition of 1% 24.88 MPa was recorded while 1.5% recorded 30.57 MPa, which was 65.10% and 102.85% higher than the control sample respectively. Beyond 1.5% dosage, the concrete started to loss strength, but like other SPs used in this study, strength gained is still significantly higher than the control same. Similar behaviour can be seen with the flexural strength of concrete with SP C. Concrete achieves significant flexural strength compared to control sample with increase in SP C dosage. Up to 1.5% the gradual increase in visible, further increase in SP dosage resulted in decline in flexural strength, though the strength is still higher than control sample.

5. Conclusions

Based upon the results obtained, it can be concluded that;

- All the three local superplasticizers used in this experimental study increased the workability while at the same time also increased the compressive and flexural strengths of concrete.
- BASF 850, a synthetic polymer based superplasticizer, gave slightly better workability compared to other two superplasticizers at lower dosages, though the compressive and flexural strength achieved was significantly lower. In terms of compressive, flexural strength and workability, the optimum dosage was determined to be 2% for BASF 850.
- The workability achieved by the addition of BASF 561 was lower than BASF 850 and BASF 858 at lower dosages, but it increased significantly beyond 1%. The compressive and flexural strength achieved by BASF 561 was the highest amongst the superplasticizers. BASF 561 can be used to produce high strength concrete. The optimum dosage for BASF 561 was determined to be 1.5% at which significantly higher workability and strength was achieved.
- A linear increase in workability was achieved with the BASF 858 superplasticizer. The optimum dosage was determined to be 1.5% in terms of compressive, flexural strength and workability, where almost double compressive strength was achieved with relatively good workability.

6. Conflicts of Interest

The author declares no conflicts of interest.

7. References

[1] Sohu, S., Ullah, K., Jhatial, A. A., Jaffar, M. and Lakhiar, M. T. “Factors Adversely Affecting Quality in Highway Projects of Pakistan.” International Journal of Advanced and Applied Sciences 5, no. 10 (October 2018): 62–66. doi:10.21833/ijaas.2018.10.009.

[2] Lakhiar, Muhammad Tahir, Samiullah Sohu, Imtiaz Ali Bhatti, N. Bhatti, Suhail Ahmed Abbasi, and Muhammad Tarique. "Flexural Performance of Concrete Reinforced by Plastic Fibers." Engineering, Technology & Applied Science Research 8, no. 3 (2018): 3041-3043.

[3] Khitab, Anwar, Muhammad Tausif Arshad, Faisal Mushtaq Awan, and Imran Khan. "Development of an acid resistant concrete: a review." International Journal of Sustainable Construction Engineering and Technology 4, no. 2 (2013): 33-38.

[4] Asian Development Bank, "Infrastructure for supporting inclusive growth and poverty reduction in Asia", Mandaluyong City, Philippines: Asian Development Bank, (2012).

[5] Aprianti S, Evi. "A Huge Number of Artificial Waste Material Can Be Supplementary Cementitious Material (SCM) for Concrete Production – a Review Part II." Journal of Cleaner Production 142 (January 2017): 4178–4194. doi:10.1016/j.jclepro.2015.12.115.

[6] Shete, M. N., Bhandari, P. S., Rikame, S. S. and Pathak, P. M. "Curing Acceleration of Concrete Bricks by Using Chemical Admixture", International Journal of Engineering Research and Applications, Vol. 3, No. 5, (2013): 611 – 614.

[7] Okamura, Hajime, and Masahiro Ouchi. "Self-Compacting Concrete." Journal of Advanced Concrete Technology 1, no. 1 (2003): 5–15. doi:10.3151/jact.1.5.

[8] ASTM C494/C494M-17, "Standard and Specification for Chemical Admixtures for Concrete", ASTM International, West Conshohocken, PA, 2017. doi: 10.1520/C0494_C0494M-17

[9] Anitha, J., Pradeepa, S., Soni, L. and Rakshit, K. B. "Influence of Admixtures on Behavior of Concrete", International Journal of Research in Advent Technology, Vol. 4, (2016): 16 – 23.

[10] Jhatial, Ashfaque Ahmed, Samiullah Sohu, Nadeem-ul-Karim Bhatti, Muhammad Tahir Lakhiar, Raja Oad, et al. "Effect of Steel Fibres on the Compressive and Flexural Strength of Concrete." International Journal of Advanced and Applied Sciences 5, no. 10 (October 2018): 16–21. doi:10.21833/ijaas.2018.10.003.

[11] Shah, S. N. R., Aslam, M., Shah, S. A. and Oad, R. "Behaviour of Normal Concrete using Superplasticizer under Different Curing Regimes", Pakistan Journal of Engineering and Applied Sciences, Vol. 15, (2014): 87 – 94.

[12] Alsadey, S. "Effect of Superplasticizer on Fresh and Hardened Properties of Concrete", Journal of Agricultural Science and Engineering, Vol. 1, No. 2, (2015): 70 – 74.

[13] Dumne, S. M. "Effect of superplasticizer on fresh and hardened properties of self-compacting concrete containing fly ash." American Journal of Engineering Research 3, no. 3 (2014): 205-211.

[14] Shi, Chen, Ting-shu He, Ge Zhang, Xi Wang, and Yanyan Hu. "Effects of Superplasticizers on Carbonation Resistance of Concrete." Construction and Building Materials 108 (April 2016): 48–55. doi:10.1016/j.conbuildmat.2016.01.037.

[15] Mardani-Aghabaglou, Ali, Murat Tuyan, Gökhan Yılmaz, Ömer Arıöz, and Kambiz Ramyar. "Effect of Different Types of Superplasticizer on Fresh, Rheological and Strength Properties of Self-Consolidating Concrete." Construction and Building Materials 47 (October 2013): 1020–1025. doi:10.1016/j.conbuildmat.2013.05.105.

[16] Yang, Lei, Erol Yilmaz, Junwei Li, Hui Liu, and Haiqiang Jiang. "Effect of Superplasticizer Type and Dosage on Fluidity and Strength Behavior of Cemented Tailings Backfill with Different Solid Contents." Construction and Building Materials 187 (October 2018): 290–298. doi:10.1016/j.conbuildmat.2018.07.155.

[17] Nematollahi, Behzad, and Jay Sanjayan. "Effect of Different Superplasticizers and Activator Combinations on Workability and Strength of Fly Ash Based Geopolymer." Materials & Design 57 (May 2014): 667–672. doi:10.1016/j.matdes.2014.01.064.

[18] ASTM C143/C143M-15a, "Standard Test Method for Slump of Hydraulic-Cement Concrete", ASTM International, West Conshohocken, PA, 2015. doi: 10.1520/C0143_C0143M-15A.

[19] ASTM C39/C39M-18, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", ASTM International, West Conshohocken, PA, 2018. doi: 10.1520/C0039_C0039M-18.

[20] ASTM C78/C78M-18, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", ASTM International, West Conshohocken, PA, 2018. doi: 10.1520/C0078_C0078M-18.