Research on Mechanical Properties and Applications of High-Performance Concrete

Yuxiang Cheng [1,*], Yinuo Li [2], Shubo Pang [3], Xinghao Zhao [4]

[1] College of Design, University of Minnesota, Minneapolis, USA

[2] Technology of Creative College, Virginia Tech, Blacksburg, USA

[3] Department of exploration technology and engineering, Hebei Geo University, Shijiazhuang, China

[4] Brunel London School North China University of Technology, North China University of Technology, Beijing, China

* Corresponding Author Email: Cheng969@umn.edu

Abstract. In recent years, with the rapid pace of civil engineering and the progress of building materials technology, high performance concrete (HPC) has been widely used. With the use of admixtures and additives, the quality and control of HPC become more complicated. Therefore, how to control and evaluate the quality of HPC has become a research hotspot in the field of architecture. This paper is mainly about the performance analysis and application research of HPC. First of all, the advantages of HPC are demonstrated by comparing it with ordinary concrete. In the process of preparing HPC with good mechanical properties, the preparation requirements of cement, the selection of fine aggregates and admixtures are described systematically. Then the wide application of HPC in various buildings is listed. At the same time, it points out the control points of mixing and pouring of HPC in construction, which provides an effective reference for the development of HPC industry in the future.

Keywords: High performance concrete, durability, quality control, application.

1. Introduction

High Performance Concrete (HPC) is a concept first proposed by the American Concrete Institute in 1990, which consists of raw materials such as cement, aggregates, water, active fine admixtures and highly efficient admixture. The obvious advantage is its good workability, high strength, and durability, etc. The CECS207 (2006) Technical Specification for the Application of HPC explains HPC as the concrete produced by applying ordinary materials and production processes that can ensure all the mechanical properties required for concrete structures, with better durability, higher workability, and higher strength. The CECS207: 2006 "HPC Application Technical Specification" interprets HPC as the application of general materials and production processes to ensure the mechanical properties required by concrete structures, as well as outstanding durability, higher workability and higher volume stability. Today's experts and scholars on HPC also have different opinions, most of the differences are on the durability, workability, strength and other properties of different emphasis [1].

2. Difference between HPC and Ordinary Concrete

2.1. Advantages of HPC

Compared with ordinary concrete, HPC has better workability, higher strength and better durability.

(1) High workability

Workability has a great influence on the use of concrete. High workability is to ensure that the concrete homogeneous and reliable and good durability of the premise, while high workability is also conducive to shorten the construction period, improve the construction environment, improve environmental protection. In the long run, high workability increases the possibility of mechanization and automation of concrete production and construction, and HPC has better workability than ordinary concrete, with higher fluidity of mix, good uniformity and self-compactness, which brings a vast improvement in the construction environment, increases the use of mechanization, and reduces the duration of the construction period, and enhances the protection of the environment.

(2) Durability

Concrete durability plays a vital part in the operation life of the building, compared with ordinary concrete, HPC durability is good, the advantages of this feature are very obvious, its frost resistance, impermeability, carbonation resistance, corrosion resistance are better than the property of ordinary concrete, HPC's long service life, suitable for use in harsh conditions of large-scale building structures and special protection works. HPC structure can be used normally for more than 50 years, which is 3~10 times of normal concrete, which greatly improves the service life of buildings and structures [2].

(3) High strength, high volume stability

HPC strength is generally high, compressive strength has reached a maximum of 200MPa, has a high seepage resistance, and often early strength is also high. As a result of low water consumption and cement. Low water-cement ratio, low porosity within the structure, densification is improved, concrete gradation is improved, internal densification is improved, low heat of hydration in the early stages of concrete hardening, and there is very low shrinkage deformation after hardening. Compared with ordinary concrete, HPC has improved strength and volume stability.

(4) Small shrinkage, low creep

The total shrinkage of HPC is inversely proportional to its strength within a certain range, and the total shrinkage decreases as the strength increases. Relative humidity and ambient temperature have a greater effect on the shrinkage properties of HPC. Due to less water consumption, good fluidity, high resistance to segregation and thus superior filling properties, the creep deformation of HPC is significantly lower than that of common concrete.

2.2. Difference Characteristic Indexes and Composition Materials

2.2.1 Different characteristic indexes

Ordinary concrete regards compressive strength as the most basic characteristic, namely, strength is the sole indicator required for the design and production of ordinary concrete proportions; while HPC considers durability as the key target, as well as strength, workability and volume stability. Although the development of HPC is based on ordinary concrete, but the characteristics of the two indicators are very different.

2.2.2 Different composition materials

Ordinary concrete is to cement, coarse and fine aggregates and water as raw materials; and HPC is in the four components on the basis of a large number of chemical additives and mineral admixtures, so that its performance has been a qualitative change. Admixtures, mineral admixtures and other auxiliary ingredients have been recognized as indispensable components of HPC.

(1) Admixture is no longer a single species, but to the direction of compounding, composite development. Such as: high-efficiency water reducing agent is a surfactant, with a high degree of dispersion of cement particles, to eliminate the role of flocculation structure, to solve the low water-cement ratio and the contradiction between the workability of the concrete water-cement ratio breakthrough in the theoretical water-cement ratio (0.38) of the desire to become a reality.

(2) Mineral admixture also from the simple use of unprocessed single species, to the grinding of deep processing, composite direction. Ordinary concrete mainly uses natural volcanic ash materials and raw industrial by-products (i.e., fly ash, water quenching slag, etc.) as admixtures, due to insufficient fineness and poor quality, which makes the degree of volcanic ash reaction is limited, and its main contribution is the micro-aggregate effect and filling effect. For HPC, on the other hand, silica fume of good quality or reprocessed industrial by-products are used as admixtures. Because of

the small fineness and very high activity, its main effects are: it can replace a certain proportion of cement to increase the volume stability of concrete; modify the grading of concrete and boost the degree of densification; it can react with the weak crystalline $Ca(OH)_2$ in the hydration products of cement in the volcanic ash reaction to form a hydrated calcium silicate gel that is profit to strength and durability, and it has the effect of inhibiting harmful chemical reactions [3].

2.2.3 Different water-cement ratio

This is ordinary concrete and HPC in terms of durability and strength of the essential difference between the two demarcation of the theoretical water-cement ratio of 0.38 (or 0.4). Ordinary concrete is generally used 0.4 ~ 0.8 of the water-cement ratio; and HPC as a result of the mixing of high-efficiency water-reducing agent to lower the water-cement ratio, that is, not greater than 0.38 (or 0.4), or not greater than 0.2.

As HPC mostly adopts low water-cement ratio 3, there is no excess water in the mix, the number of capillary pores is greatly reduced after hardening of concrete, and the pore size of capillary pores is also smaller than that of ordinary concrete (generally in the range of 10~50nm or smaller). In addition, the particle size of the ultrafine admixture is smaller than the cement particles, which can fill the gap between the cement particles, improve the grading between the powder materials, and further reduce the number of capillary pores in the concrete. The joint effect of the above factors, so that HPC formed a dense microstructure, a variety of harmful media is difficult to enter the interior, durability and strength increased significantly.

2.2.4 Different microstructure

Concrete is a kind of porous body with different pores. The number of capillary pores and gels is an important factor in determining the strength and durability of concrete. The fewer the capillaries, the denser the concrete and the better the durability, and vice versa; while the higher the number of gels, the higher the strength of concrete, and vice versa. Compared with ordinary concrete, HPC adopts a low water-to-cement ratio, which significantly reduces the number of pores after hardening; and ultrafine admixture improves the grading of powder aggregate, which also greatly reduces the number of pores, so that HPC forms a highly dense microstructure. In addition, the activity of ultrafine dopant is large, and the volcanic ash reaction is strong, which consumes a large amount of $Ca(OH)_2$ and produces a higher amount of gel, which makes the strength improve; meanwhile, the reduction of $Ca(OH)_2$ also improves the corrosion resistance of HPC.

2.2.5 Different macroscopic properties

Compared with ordinary concrete, HPC has high strength, high durability and high workability and other macroscopic properties. HPC's high durability is more advantageous than high strength, due to the reduction of capillary pores and powder reasonable grading so that its microstructure reaches a fairly dense state, it is difficult for the outside world to invade the harmful media, even if the sea water corrosion of the offshore drilling platforms and bridges across the sea can also achieve a high degree of durability. Tsinghua University research shows that ", after reasonable design, HPC in the marine environment can achieve more than 100 years of durability, the durability of the high is difficult to reach the ordinary concrete [4].

3. Material Selection and Mechanical Properties of HPC

3.1. HPC Raw Materials

3.1.1 Cement

Generally speaking, for ordinary concrete only need to consider the strength of cement, but for HPC on the performance of cement has special requirements. First of all, the requirements of rheology, HPC on the performance of cement, in addition to the minimum fluidity, should also ensure that the cement in the low water-cement ratio can also be hydration reaction, so that the cement stone is more compacted [5].

Ready-mixed concrete enterprises mainly use ordinary silicate cement and silicate cement. Cement quality performance is good or bad, must be measured from the cement in the concrete performance and application of two aspects, cement standards should also have a "concept".

The cement standard should also have a "concept" of conversion. Concrete technology to high-performance development, the need for cement has to adapt to the quality characteristics of the high performance demands of concrete, in order to reduce the unit water consumption of concrete. It is suggested that ordinary silicate cement and silicate cement standards should be added to the following indicators to adapt to the requirements of ready-mixed concrete enterprises.

(1) There should be cement standard consistency water consumption index (≤26.0%). Consider cement clinker in the specific surface area of 350m2/kg, the standard consistency of water consumption in 24% ~ 25%, even if the ordinary silicate cement allows no more than 15% of the mixed material mixed. It is also necessary to strictly control the standard consistency of cement water consumption <26.0%.

(2) Propose cement and additives compatibility requirements. At present, we put forward to the cement factory, according to the recommended dosage of water reducing agent mixed with cement net slurry flow ≥180mm to meet the use of requirements.

(3) There should be factory cement temperature control requirements (<65℃). If we do not pay attention to the performance requirements of the above 3 aspects, it is difficult to improve some of the apparent common problems in the cement production process.

HPC quality requirements for cement, generally have the following three aspects: reasonable particle composition; better uniformity and stability; and ease of use and water demand. Regarding the reasonable particle composition, the measure generally adopted is to add some finely ground mixing materials to adjust the particle composition of cement on the one hand, and to make up for some deficiencies of clinker in performance on the other hand.

3.1.2 Mixing water

When mixing concrete, mixing water is added to give the concrete fluidity, and hydration reaction with cement occurs, so that the concrete sets and hardens. Thus the mixing water has a great influence on the setting, hardening, volume change and strength of the concrete mix. The water used for mixing concrete must not contain substances that have harmful effects on the reinforcement in the concrete. Generally use cleaner river water, well water, tap water, lake water and stream water, etc., but pH>4. And do not use factory wastewater, swamp water and hardness of water; prohibit the water contains acids, sugars, fats and other harmful substances.

The technical requirements for concrete mixing water in the Standard for Concrete Mixing Water (JGJ63-2006) are as follows.

(1) Effect on setting time: Use drinking water and water to be tested to carry out cement setting time test. The difference between the initial and final setting time of the two shall not exceed 30min, and shall conform to the provisions of national standards.

(2) On the impact of compressive strength: mortar or concrete mixed with water to be tested under standard conditions of maintenance of 28d age compressive strength, shall not be less than 90% mixed with drinking water.

3.1.3 Fine aggregate

Fine aggregate should be clean natural medium-coarse sand with good grading and hard texture, the quality of which shall meet the requirements of sand and gravel standards for ordinary concrete. The degree of sand coarseness has obvious influence on the concrete strength, usually, the coarser the sand, the higher the concrete strength. The higher the strength grade of concrete, the higher the modulus of fineness of sand used for preparation.

3.1.4 Fine admixture

The purpose of using mineral fine admixtures in the formulation of HPC is to inhibit alkali aggregate reaction in concrete. Prof. Wu Zhongwei pointed out that mineral fine admixtures, as the main constituent materials of HPC, can make the performance of conventional concrete fundamentally changed [6]. HPC preparation process, in order to promote the transformation of cement hydration products, can be mixed with an appropriate amount of active mineral fine admixture, the pore structure of hardened concrete can be improved, and densification improved. It is worth noting that the use of mineral fine admixture is not so simple. Its species and the amount of mixing should be determined on a case-by-case basis. Relevant research shows that the effect of more than two kinds of mineral fine admixture mixing is better than the sum of their individual use, that is, there is a superposition effect.

3.1.5 Admixtures

In the concrete mixing process and can be required to improve the properties of concrete materials called admixtures, usually, the amount of mixing less than or equal to 5% of the mass of cement. So far, there are many kinds of admixtures and their functions are different. According to the function of the admixture can be divided into early strength agent, water reducing agent, quick-setting agent, expansion agent, air-entraining agent and so on. The development of concrete technology cannot be separated from the admixture, in the ordinary or special requirements of the concrete, the admixture is becoming indispensable. When choosing, attention should be paid to the adaptability of admixtures and cement. Tests have shown that different varieties of cement, the same admixture on the concrete fluidity and strength and other properties of the improvement of the difference is very large; different varieties of cement, mixed with admixture on the concrete setting time and slump loss of the impact is also different; different manufacturers of the same varieties and strength levels of cement activity is not the same. Therefore, the role of admixture is related to the adaptability of cement, should be done, including water reduction and slump loss through the time of the two-adaptability test, preferred and good adaptability of cement admixture [7].

Under the condition that the slump of concrete is basically the same, the admixture that can reduce the water consumption is called water reducing agent, also called plasticizer. According to the water reducing capacity is divided into ordinary water reducing agent and high efficiency water reducing agent. High-efficiency water reducing agent has stronger water reducing ability than ordinary water reducing agent and lower air-entraining capacity, also called superplasticizer or fluidizer. According to the role of water reducing agent, it can be divided into standard type, early strength type, retarder type and air-entraining type, etc. It should be selected according to the needs and technical requirements of concrete. The main technical properties of water reducing agent are gas content ratio, water reduction rate, setting time difference and so on. The use should be based on the selected varieties and types, according to the standard provisions of the test its relevant properties. The main properties and economic and technical indicators of water reducing agent are as follows.

(1) Improvement of the fluidity of the mix

Under the premise of unchanged water consumption, water reducing agent can increase the slump of concrete by 100~200mm.

(2) Reducing cement dosage and cost

If the concrete strength remains unchanged, that is, the water-cement ratio remains unchanged, the water consumption of water and mud can be reduced, cement savings of 10% to 15%, the cost of concrete is reduced.

(3) Slowing down the rate of exothermic hydration, and delaying the emergence of exothermic peak

Under the condition of the same strength and durability requirements, the amount of cement can be reduced, reducing the total heat of hydration. The incorporation of retarder-type water reducing agent is conducive to reducing the generation of cracks in mass concrete under the action of temperature stress.

(4) Improvement of durability

After the water reducing agent is incorporated, the fluidity of the fall compound is improved, it is easy to pour dense, reduce the water consumption of concrete, the occurrence of capillary pores inside the concrete as well as the phenomenon of water seepage, so that the impermeability and frost resistance of concrete can be improved.

3.2. Mechanical Characteristics of HPC Materials

The performance of concrete in mechanical trials of HPC materials is determined by the percentage of mineral admixtures. The selection of mineral admixtures involves choosing a combination of 60% mineral powder and 40% fly ash, based on the evaluation of compressive strength, flexural strength, and detailed analysis of the component percentages. The composite mineral admixture consisting of fly ash and mineral powder shall be manufactured in accordance with the specified proportion of mineral powder. The ratio of fly ash to the total mixture is 6:4. An investigation will be conducted to assess the impact of various grades of composite mineral admixtures on the mechanical characteristics of concrete. The objective is to identify the best range of admixture that will result in high-performance concrete (HPC) with superior mechanical qualities [8].

The test involved setting the mixing amounts of composite mineral admixtures at 0%, 15%, 30%, 45%, and 60%, respectively. The term "mixing amount" primarily pertains to the ratio of the combined quantity of cement and mineral admixtures. Table 1 displays the mix proportions of various quantities of mineral powder fly ash composite mineral admixtures. The aggregate weight of cementitious materials is 470kg, the ratio of water to binder is 0.33, and the proportion of sand is 38%. The determination of concrete pouring temperature should be based on the prevailing weather conditions in the area and the specific requirements of the concrete construction project. In general, the optimal temperature range for pouring concrete is between 5°C to 35°C. Concrete's setting time is extended when the temperature drops below 5°C, leading to a reduction in its strength. Conversely, if the temperature exceeds 35°C, the concrete sets too quickly, making it prone to cracking and deformation. [9, 10].

Table 1. Mix proportions of mineral powder–fly ash composite mineral admixture with divergent dosages

Mixing Amount (%)	Amount of per Square Meter (kg/m^3)						
	Cement (kg)	Fly Ash (kg)	Mineral Powder (kg)	Sand (kg)	Gravel (kg)	Water (kg)	Additive (kg)
0	470	0	0	500	1000	165	4.8
15	400	29	41	500	1000	165	4.8
30	350	59	82	500	1000	165	4.8
45	258	91	121	500	1000	165	4.8
60	188	117	165	500	1000	165	4.8

The experiment involved testing the mechanical qualities of concrete with various mineral admixtures, including mineral powder and fly ash. To obtain the experimental procedure, consult the Test Method for Durability and Long-term Mechanical Properties of Concrete outlined in GB/T 50082-2009. The impact of the quantity of compound mineral additive on the mechanical characteristics of concrete is demonstrated in Table 2.

Table 2. Effect of complex mineral admixture amount on workability of concrete

Mineral Powder-Fly Ash (%)	Slump (cm)	Expansion (cm)	30 min Slump Loss (cm)	60 min Slump Loss (cm)
100-0	17	35	5.5	7.5
60-40	20	41	3.3	5.3
50-50	24	52	2.6	4.7
40-60	24	56	2.6	4.7
0-100	22	56	2.2	4.0

Table 3 demonstrates that the compressive and flexural strength of concrete gradually diminishes initially and then rapidly declines as the quantity of composite mineral admixture increases. Concrete exhibits no discernible alteration in strength as the quantity ranges from 0% to 30%. Concrete's compressive strength and flexural strength will rapidly fall when the additive content above 30%. The fundamental reason for this is that the hydration of cement enhances the reactivity of mineral powder and fly ash in the composite mineral additive over time. This, in turn, stimulates the secondary hydration reaction of free calcium oxide and strongly alkaline C-S-H, leading to an improvement in the strength of the concrete. Hence, the optimal composition of the mineral admixture for C50 HPC should range from 30% to 45%. The typical proportion of mineral powder-fly ash composite mineral additive is 35%, taking into account the concrete's stability and economic cost. [11].

Table 3. Influence of composite mineral admixtures on mechanical properties of concrete

Mineral Powder-Fly Ash (%)	3d Compressive Strength (MPa)	7d Compressive Strength (Mpa)	28d Compressive Strength (Mpa)	3d Flexural Strength (Mpa)	7d Flexural Strength (Mpa)	28d Flexural Strength (Mpa)
100-0	30	42	47	4.6	5.7	6.0
60-40	28	43	47	4.1	5.2	5.9
50-50	27	39	44	3.8	4.8	5.3
40-60	27	36	42	3.5	4.3	4.9
0-100	24	34	40	3.1	3.7	4.7

4. Application and Performance of HPC

4.1. High Rise Structures

Utilizing High Performance Concrete (HPC) in the construction of high-rise structures results in decreased dead load, deflection, vibration, and maintenance requirements for the concrete, as depicted in Fig. 1.

Figure 1. HPC Used in Tall Building

4.2. Bridges

The utilization of High-Performance Computing (HPC) in the construction of bridge constructions yields numerous enhancements in their structural integrity. For example, it enhances the resilience of the structures and hence extends their longevity, as depicted in Fig. 2. Furthermore, the utilization of High Performance Concrete (HPC) enables the construction of longer span prestressed concrete girders. This is due to the fact that using concrete of this nature results in a reduced loss in pre-stress, allowing for higher allowed stress and a smaller cross-section to be attained. In addition, reducing the size of structural elements results in a decrease in weight, which in turn makes handling more cost-effective. The incorporation of pozzolanic elements such as silica fume and fly ash improves the structure's resistance to chloride.

Figure 2. HPC Used in Flyover Construction

4.3. Highway Pavements

The utilization of High Performance Concrete (HPC) in highway pavements has significant advantages. These include the capacity to achieve early strength gain, reduced permeability, improved resistance to abrasion caused by steel studded tires, and enhanced durability against freeze-thaw cycles, as demonstrated in Fig. 3. The HPC can also be utilized for expedient pavement restoration in cases of deterioration.

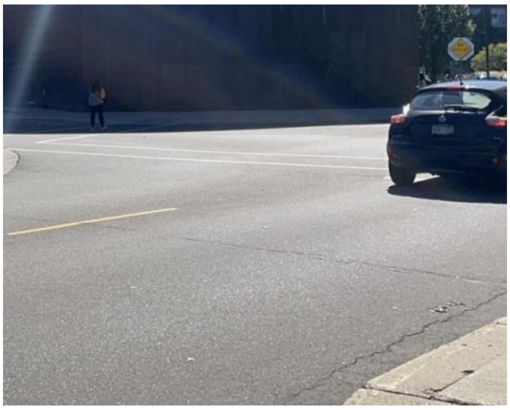

Figure 3. Highway Construction Using HPC

4.4. Hydropower Structures

High-performance concrete (HPC) has been utilized to reinforce the spillway, diversion tunnel, headrace tunnel, slit flushing tunnel, and tailrace tunnel. This application enhances the structural capabilities of these components to effectively manage high water velocities and significant silt loads, as depicted in Fig. 4. The utilization of High-Performance Computing (HPC) has led to reduced maintenance requirements, on one side, and enhanced longevity, on the other hand.

Figure 4. Construction of Spillway Using HPC

4.5. Miscellaneous Applications

Steel fibers can be included into High Performance Concrete (HPC) to enhance mechanical characteristics such as dynamic and static tensile strength, energy abrasion and toughness, and fatigue resistance. Fiber-reinforced concrete has been utilized in various applications, such as pavement overlays, floor slabs, thin shells, rock slope stability, and several precast items.

5. Control Points for HPC Construction

5.1. Control of HPC Mixing

Through the application of the above project, the mixing control of HPC has gained the following experience: due to the high working requirement of HPC, the mixing of the backstage must be strictly controlled. First of all, before the construction of the background of all measuring instruments for regular testing, in particular, to test the automatic water device to ensure the accuracy of the water intake; secondly, each mixing must be carefully measured before the water content of sand and gravel, adjust the construction ratio. These two items are related to water consumption, only accurate water consumption can guarantee the water-cement ratio. In addition, the coarse and fine aggregate into the tray must be checked by a special person to ensure that the trucks are overweight. And additives by a person responsible for weighing the amount of each disk beforehand with a scale, respectively, into a prepared plastic bag, each disk into a bag.

5.2. Construction Points of HPC Pouring

One of the advantages of HPC is to simplify the construction method and save labor. Therefore, HPC foreground pouring is simpler than ordinary concrete, eliminating the need for vibration. But after the actual construction, constantly summarize the lessons learned, to ensure the quality of HPC, must also be the following points for construction control, otherwise the same cannot achieve the desired results.

(1) HPC is characterized by very small plasticity and large viscosity. The very small plasticity makes the concrete produce large lateral pressure under the action of self-weight, therefore, when using HPC, the template must be firmly installed, especially when the pouring height is high more attention should be paid to the installation of the template, and if necessary, some reinforcing measures should be taken, or pouring in sections, in order to reduce the static pressure of the fluid.

(2) When pouring HPC, attention should be paid to bottom-up pouring in a smooth layer, and some corners should be prioritized for pouring. The vertical drop distance should not be too large, and should be controlled within 5m. It must be poured in layers in accordance with the requirements of the construction specification, and each layer should not be larger than 50cm.This is mainly because without vibration, some times the air bubbles in the concrete still can not be completely exported. Pouring too thick at one time is easy to nestle the air bubbles underneath, and after demolding, it causes too many tiny bubbles on the surface of the concrete, which affects the surface appearance.

(3) Due to the HPC precast components template is relatively strong closure, the gas is not easy to discharge, if the HPC is poured too quickly, it will produce bubbles, affecting the appearance of the precast components and the internal quality. In general, when using HPC to produce precast components, the pouring speed should not be too fast, and should not be greater than the flow rate of HPC under its own weight.

6. Conclusion

This paper studies the mechanical properties and applications of HPC, and obtains the following main conclusions: (1) Due to strict material selection, HPC has better workability, higher strength, and better durability. (2) HPC requires a reasonable selection of mineral admixtures, fine aggregates, and admixtures in order to achieve better mechanical properties. (3) HPC is widely used in high-rise highways, bridges, hydropower buildings, etc. (4) With the continuous development of the construction industry, the demand for concrete is also increasing. HPC will continue to progress with the development of technology, and more sustainable and environmentally friendly concrete will be developed. Production methods will be more efficient, flexible, and customized.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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