Product Research and Development

Study on the Design and Optimization of the Mix Proportion for High-Grade Concrete for the Pylon of a Long-Span Suspension Bridge

Xiaoliang Zhu *, Baoan Quan, Sheng Fang, Hao Wei and Junchen Zhao

CCCC Road and Bridge East China Engineering Co., Ltd., Shanghai 201210, China.
* Correspondence: 1147263435@qq.com

Abstract: In this paper, an in-depth study was conducted on the design and optimization of the mix proportion of C55 high-fluidity pumped mass concrete for the northern pylon of the Longtan Yangtze River Bridge. During the mix proportion trial and initial adjustment phase, the W/B ratio was determined in accordance with relevant standards, and the performance indicators of the aggregates were comprehensively considered to select coarse and fine aggregates based on scientific evidence. The range of mineral admixture proportions was determined on the basis of performance and cost considerations. Through a series of experimental studies, the influence of various factors on the workability of concrete was determined, and the initial mix proportion was preliminarily established. Further exploration of the effects of cement type and functional aggregates revealed that the workability of the project cement was inferior to that of Onoda cement, but the concrete was not replaced for cost reasons. Functional aggregates can enhance concrete performance from various aspects, but may slightly reduce compressive strength. The multiobjective mix proportion was further optimized and subjected to performance verification. After functional aggregates were added to the optimized mixture, the concrete exhibited excellent workability and met the strength requirements. Thermal insulation aggregates effectively mitigated an increase in concrete temperature, whereas heat-storage aggregates provided good initial temperature control during pouring. Through more than 20 sets of experiments, multistep optimization, and verification, the key factors and their mechanisms in mix proportion design were clarified. This study provides a systematic methodology and practical basis for the design of high-strength, high-fluidity mass concrete, ensuring the safety and durability of projects.

Keywords: high-grade concrete; high-strength; high fluidity; mix proportion design; optimization; multiobjective performance

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1 Introduction

The north pylon of the Longtan Yangtze River Bridge is designed as a portal frame structure with a total height of 235.5 m. The pylon columns are designed as rectangular box sections, with a 6 m solid section at the base. The columns are made of C55 high-fluidity pumped concrete, which is characterized by high strength, high pumpability, high surface quality, and large volume. For high-strength, high-pumpability (referred to as high pumping distance), large-volume, and high-homogeneity concrete, high strength implies a low water–binder (refer to W/B) ratio and high cementitious material content. For high pumpability, excellent workability is required, which necessitates a high fly ash content. A large volume implies a low cement content and high admixture content, whereas high homogeneity refers to a uniform appearance and color, meeting the requirements of fair-faced concrete with relatively low fly ash content. Overall, concrete mix proportion design is a systematic engineering task with stringent demands for detailed design parameters. The concrete for the north pylon of the Longtan Yangtze River Bridge must meet multiobjective performance requirements, including those related to workability, mechanical properties, deformation properties, and thermal properties. It is essential to keep various parameters within reasonable ranges and ensure stability during pouring. In this paper, the mechanical and workability properties of concrete are explored through multiple mix proportion experiments, and further research is conducted on the design and optimization of high-grade, large-volume concrete on the basis of multiobjective performance. The design process, research methods, and experimental conclusions for C55 high-fluidity pumped mass concrete are summarized.

2 Mix Proportion Trial and Initial Adjustment

2.1 Preliminary Selection of Mix Proportion Parameters

(1) Water–Binder Ratio

Based on the “Specification for Mix Proportion Design of Ordinary Concrete” (JGJ 55—2011) [1] and the “Code for Durability Design of Concrete Structures in Highway Engineering” (JTG/T 3310—2019) [2], the design strength is C55, and the trial strength $f_{cu,0}$ is determined as follows:

$$f_{cu,0} \geq f_{cu,k} + 1.645\sigma \tag{1}$$

where $f_{cu,k}$ and σ are the standard value of the concrete cube compressive strength and the standard deviation of the concrete strength, respectively. On the basis of Equation (1), the trial strength $f_{cu,0}$ is calculated as 64.8 MPa, rounded to 65 MPa.

The water–binder ratio W/B is calculated according to the Bolomey formula as follows:

$$W/B = \frac{\alpha_a \gamma_f \gamma_s f_{ce}}{f_{cu,0} + \alpha_a \alpha_b f_{ce}} \tag{2}$$

In accordance with the “Specification for Mix Proportion Design of Ordinary Concrete” (JGJ 55—2011), for crushed stone, $\alpha_a = 0.53$ and $\alpha_a = 0.20$, the fly ash content is 30%, and the influence coefficient γ_f is obtained from the specification table. The S95 grade slag powder content is 15%, and the influence coefficient γ_s is obtained from the specification table. f_{ce} is the 28-day strength of the cement. The cement used in the experiment is Grade 52.5, with a surplus coefficient of 1.1. On the basis of Equation (2), the W/B ratio is calculated as 0.323.

(2) Coarse and Fine Aggregates

The selection of aggregates was primarily based on the following aspects: mineral composition and performance of the aggregates, content of harmful substances, surface shape and properties of the particles, aggregate gradation, and maximum particle size of the coarse aggregates.

(3) Determination of Mineral Admixture Ratio

Research shows that a wide particle size distribution enhances the compactness and reduces the pore structure of cement mortar or concrete, which is improves strength [3]. Currently, the specific surface area of slag powder and fly ash generally exceeds 400 m^2/kg, with some even reaching 600 m^2/kg. When slag powder and fly ash are combined with coarser Portland cement, the overall particle size distribution of the cementitious materials can be optimized. Therefore, the addition of fly ash and slag powder helps broaden the particle size distribution of powder materials. High-quality fly ash can produce active morphological and microaggregation effects in concrete. Adding slag powder as an admixture significantly improves the density of cement concrete [4], optimizes the overall particle size distribution of cementitious materials, and enhances the workability, water retention, pumpability, and finishing properties of concrete. It also reduces hydration heat, minimizes shrinkage, and improves the durability of concrete.

In accordance with the “Code for Durability Design of Concrete Structures in Highway Engineering” (JTG/T 3310—2019) and Appendix B of the “Standard for Design of Concrete Structure Durability” (GB/T 50476—2019) [5], the fly ash content should not exceed 30%. To balance good workability and economic efficiency while ensuring concrete strength and durability, the admixture ratio is selected to be 35–45%.

2.2 *Determination of Mix Proportion Parameters Based on Workability*

Based on the aforementioned summary, a W/B ratio of 0.323 was selected, with the water content controlled between 145–160 kg to ensure that the total cementitious material content remained below 500 kg. Considering hydration heat, economic factors and engineering experience, the cementitious material content can be as low as 450 kg, with the total admixture content ranging from 35% to 45%. The sand-to-total aggregate ratio (abbreviated as the sand ratio, S_P) by mass is between 38% and 45% (40–47% by volume). To explore the most suitable concrete mix proportions, multiple trial mix experiments were conducted by varying the sand ratio, mineral admixture proportion, and water-reducing agent content.

2.2.1 Influence of Cementitious Material Content on Concrete Workability

To meet high strength requirements, a low W/B ratio and high cementitious material content are necessary. By varying the cementitious material content (456–500 kg/m^3), the influence of cementitious material content on concrete workability was studied. The mix proportions for different cementitious materials are shown in Table 1, and the corresponding workability results are presented in Table 2.

Table 1 Mix proportions for different cementitious materials

Group	W/B	Water (kg)	Cementitious material (kg)	Cementitious material ratio (%)			Sand ratio S_P (%)		Water-reducing agent (%)
				Cement	Fly ash	Slag powder	Mass	Volume	
B500	0.32	160	500	65	15	20	45	47	1.00
B480	0.33	160	480	65	15	20	44	47	1.20
B456	0.32	146	456	55	25	20	44	46	1.00

Table 2 Workability of concrete with different cementitious material contents

Group	Slump (mm)	Spread (mm)	Workability characteristics	7-day compressive strength (MPa)
B500	250	620	No bleeding, bottom segregation, rapid slump loss	68.4
B480	220	600	Significant bleeding, bottom segregation, poor cohesion	60.5
B456	210	550	Slight bleeding, bottom segregation, rapid slump loss	59.3

The results show that the 7-day compressive strength of all three groups exceeds 55 MPa, but the workability of each group is suboptimal, with rapid slump loss. As the cementitious material content increases, the slump and spread of the concrete improve, but a higher cementitious material content also increases costs. In Group B456, the ratio of cement, fly ash, and slag powder is 55:25:20, with reduced cement content and increased fly ash content compared with those of the other groups. This results in improved bleeding resistance.

2.2.2 Influence of Mineral Admixture Ratio on Concrete Workability

Increasing the fly ash content enhances the fluidity and water retention of concrete, which helps mitigate slump loss [6]. Slag powder particles are irregular in shape, which improves later-stage strength but increases water absorption, potentially exacerbating early slump loss. Reducing the slag-to-powder ratio can help minimize water loss [7]. Considering the suboptimal workability in the previous experiments, Groups 4–6 were added based on Group 3 (B456), maintaining a cementitious material content of 456 kg and a total mineral admixture (fly ash and slag powder) content of 45%. The proportions of fly ash and slag powder, as well as the water-reducing agent content, were adjusted to analyze the influence of mineral admixtures on the workability of the concrete. Additionally, Group 7 (Group 25FA15SL) was introduced to test a newly formulated water-reducing agent, with a mineral admixture content of 40%. The mix proportions are shown in Table 3, and the workability results are presented in Table 4 and Figure 1.

Table 3 Mix proportions for different mineral admixture ratios

Group	W/B	Water (kg)	Cementitious material (kg)	Cementitious material ratio (%)			Sand ratio S_P (%)		Water-reducing agent (%)
				Cement	Fly ash	Slag powder	Mass	Volume	
30FA15SL	0.32	146	456	55	30	15	40	42	1.30
25FA20SL-1	0.32	146	456	55	25	20	40	42	1.30
25FA20SL-2	0.32	146	456	55	25	20	40	42	1.00
25FA15SL	0.35	153	440	60	25	15	38	40	1.30

Table 4 Workability of concrete with different mineral admixture ratios

Group	Slump (mm)	Spread (mm)	Density (kg/m^3)	Workability characteristics
30FA15SL	235	580	2,446	Slight bleeding, bottom segregation
25FA20SL-1	235	540	2,470	Slight bleeding, bottom segregation
25FA20SL-2	200	530	/	Bleeding, bottom segregation, rapid slump loss
25FA15SL	230	500	2,507	1-h spread: 530 mm, slump rebound

The proportion of mineral admixtures also affects concrete workability. Owing to the morphological effect of fly ash, increasing its content improves fluidity, whereas increasing the slag powder content reduces fluidity. When the fly ash content is 30% and the slag powder content is 15%, the overall performance of the concrete is better, but the slump retention is poor, with rapid slump loss and slight bleeding and bottom segregation. To meet the requirements for a large volume and high pumping distance, the mineral admixture ratio in the mix was determined to be 45%, with a fly ash-to-slag powder ratio of 30:15.

Figure 1 Workability of concrete with different mineral admixture ratios

In Group 7 (Group 25FA15SL), a newly formulated water-reducing agent was used, which increased slump retention and air entrainment. Increasing the water content to 153 kg and reducing the sand ratio to 38% resulted in excellent workability, with no bleeding or bottom segregation. However, the water–binder ratio of 0.35 exceeded the requirements of the "Code for Durability Design of Concrete Structures in Highway Engineering" (JTG/T 3310—2019), necessitating further optimization.

2.2.3 Influence of the Sand Ratio on Concrete Workability

By varying the sand ratio, the influence of sand ratio on the workability of concrete was studied. The mix proportions are shown in Table 5, and the workability results are presented in Table 6 and Figure 2.

Table 5 Mix proportions for the various sand ratios

Group	W/B	Water (kg)	Cementitious material (kg)	Cementitious material ratio (%)			Sand ratio S_P (%)		Water-reducing agent (%)
				Cement	Fly ash	Slag powder	Mass	Volume	
Sp44	0.32	146	456	55	30	15	44	46	1.30
Sp40	0.32	146	456	55	30	15	40	42	1.30
Sp38	0.32	146	456	55	30	15	38	40	1.30

Table 6 Workability of concrete with different sand ratios

Group	Slump (mm)	Spread (mm)	Density (kg/m³)	Workability characteristics
Sp44	260	650	2,415	Air content >7%, poor slump retention
Sp40	270	630	2,433	Air content >7%, bleeding, rapid slump loss
Sp38	245	500	2,454	Air content >7%, slight bleeding, bottom segregation

The experiments show that concrete cohesion improves at a higher sand ratio, resulting in better slump and spread but rapid slump loss. Considering these factors, a sand ratio of 40% is selected for the mix proportion.

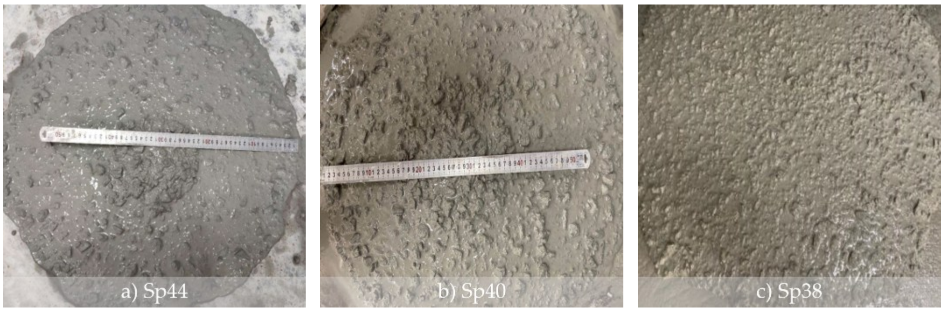

Figure 2 Workability of concrete with different sand ratios

2.2.4 Influence of Functional Aggregates on Concrete Workability

To mitigate bleeding-induced bottom segregation and improve workability, 80 kg of functional aggregates were added to the mixture, replacing 5–10 mm coarse aggregates with equal volumes. The mix proportions and workability results are shown in Tables 7 and 8.

Table 7 Mix proportions for functional concrete

Group	W/B	Water (kg)	Cementitious material (kg)	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
				Cement	Fly ash	Slag powder	Mass	Volume		
OPC	0.33	149	456	55	30	15	38	40	/	1.20
FLA-1	0.32	146	456	55	30	15	40	40	80	1.20
FLA-2	0.32	146	456	55	30	15	40	40	80	1.10
FLA-3	0.32	147	456	55	30	15	40	40	80	1.10

Note: OPC represents ordinary concrete; FLA represents function concrete.

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Table 8 Workability of concrete with functional aggregates

Group	Slump (mm)	Spread (mm)	Density (kg/m³)	Workability characteristics
OPC	230	490	2,460	Rapid slump loss
FLA-1	225	530	2,417	Slight bleeding, bottom segregation
FLA-2	230	510	2,395	No bleeding, poor workability
FLA-3	235	550	2,401	Good outcomes, no bleeding or bottom segregation

The prewetted, spherical shape of the lightweight aggregates significantly improved the workability of the concrete. Additionally, the porous nature of the aggregates mitigated slight bleeding. Group 14 (FLA-3) achieved good workability with no bleeding or bottom segregation while meeting the W/B ratio requirement.

2.2.5 Preliminary Determination of C55 Concrete Mix Proportion

For a design strength of C55, the maximum W/B ratio is determined to be 0.32 on the basis of durability design specifications. By studying the influence of the cementitious material content, mineral admixture ratio, sand ratio, and functional aggregate content on the workability of concrete, the preliminary mix proportion can be determined.

To meet the high-strength and high-fluidity requirements, the cementitious material content was set to 456 kg/m³. Increasing the fly ash content improved fluidity, so the mineral admixture ratio was set to 45%, with a fly ash-to-slag powder ratio of 30:15. A sand ratio of 40% was chosen to balance workability and slump retention. The addition of functional aggregates significantly improved workability and reduced bleeding. The preliminary mix proportions are summarized in Table 9.

Table 9 Preliminary mix proportions for C55 concrete

W/B	Water (kg)	Cementitious material (kg)	Cementitious material ratio (%)			Sand ratio S_P (%)		Water-reducing agent (%)
			Cement	Fly ash	Slag powder	Mass	Volume	
0.32	147	458	55	30	15	38	40	1.20

3 Influence of Cement Type and Functional Aggregates on the Multiobjective Performance of Concrete

3.1 Optimization of Concrete Mix Proportion Design

Owing to the high specific surface area and standard consistency water demand of the cement used in this project, it is necessary to increase the W/B ratio or the content of admixtures appropriately to meet the required fluidity. In addition to these adjustments, the workability of concrete can also be improved by changing the specific surface area of the cement (i.e., changing the cement type) or by adding functional aggregates. To study the influence of cement type and functional aggregates on the workability and durability of concrete, two control groups were established for experimentation. The mix proportions are shown in Tables 10 and 11.

Table 10 Preliminary mix proportions for C55 concrete

Group	W/B	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
		Cement	Fly ash	Slag powder	Mass	Volume		
OPC-1	0.32	55	30	15	38	40	/	1.20
FPC-1	0.32	55	30	15	40	41	80	1.15
OPC-2	0.32	55	30	15	38	40	/	1.20
FPC-2	0.32	55	30	15	40	41	80	1.11

Table 11 Concrete mix proportions (Unit: kg)

Group	W/B	Water	Cement	Fly ash	Slag powder	Sand	Coarse aggregate	Functional aggregates	Water-reducing agent
OPC-1	0.32	147	251	138	69	712	1,162	/	5.50
FPC-1	0.32	147	251	138	69	712	959	80	5.27
OPC-2	0.32	149	251	137	68	683	1,093	/	5.47
FPC-2	0.32	147	251	137	68	719	999	80	5.02

Note: OPC represents ordinary concrete, and FPC represents functional concrete. "-1" indicates the use of Onoda P·II 52.5 cement and Nanjing Yueli fly ash, whereas "-2" indicates the use of project cement and Taizhou Guodian fly ash.

3.2 Workability of Concrete

The workability of each mix proportion is shown in Table 12. When the same mix proportion was used, the workability of the groups prepared with the project cement was significantly inferior to that of the groups prepared with the Onoda cement. This is because the cement used in the project has a larger specific surface area, which resulted in greater water demand and thus poorer workability under the same mix proportion.

Table 12 Workability of concrete

Group	Slump (mm)	Spread (mm)	T50 (s)	Density (kg/m³)
OPC-1	240	600	15	2,507
FPC-1	243	550	16	2,414
OPC-2	230	490	/	2,480
FPC-2	235	550	/	2,401

Note: T50 refers to the time required for the concrete mixture to reach a spread of 500 mm after the slump cone is lifted. A shorter T50 indicates faster flow and better fluidity.

The functional aggregates, which were spherical and prewetted, were used to replace 5–10 mm coarse aggregates with equal volumes. This improved the workability of concrete, mitigated bottom segregation, and enhanced fluidity. However, the addition of functional aggregates reduced the density of the concrete. Therefore, the content of functional aggregates should be minimized while ensuring the required fluidity.

3.3 Mechanical Properties of the Concrete

3.3.1 Compressive, Flexural, and Splitting Tensile Strength

The mechanical properties of the concrete with the two mix proportions, including compressive strength, flexural strength, and splitting tensile strength, were studied after standard curing. The results are shown in Table 13.

Table 13 Strength at different ages for various mix proportions (Unit: MPa)

Group	Compressive strength			28-day flexural strength	28-day splitting tensile strength
	3-day	7-day	28-day		
OPC-1	32.9	59.6	67.0	9.15	5.64
FPC-1	35.1	47.5	56.5	8.23	5.50

By comparing the two groups, it was found that the compressive strength of the samples decreased when functional aggregates were added. The 7-day and 28-day compressive strengths were approximately 10 MPa lower than those of ordinary concrete but still meet the requirement of exceeding 55 MPa. The fracture surfaces of the compressive test samples are shown in Figure 3. For ordinary concrete, failure

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primarily occurred along the surface of the coarse aggregates, whereas for concrete with functional aggregates, failure mainly occurred within the functional aggregates.

Since functional aggregates have a lower strength and elastic modulus than cement paste does, cracks initiate and propagate on the surface of the functional aggregates, leading to aggregate failure [8,9]. In this experiment, functional aggregates were used in a saturated surface-dry (SSD) state, whereas ordinary aggregates were used in a dry state. On the basis of the water absorption rate of 0.91% for ordinary aggregates in a saturated surface-dry state, the actual water content difference was at least 10.0 kg/m³, which contributed to the reduction in the compressive strength of functional concrete. When functional aggregates are used, the selection of aggregates with greater strength is recommended, and their existing water content should be accounted for in the mix proportion design.

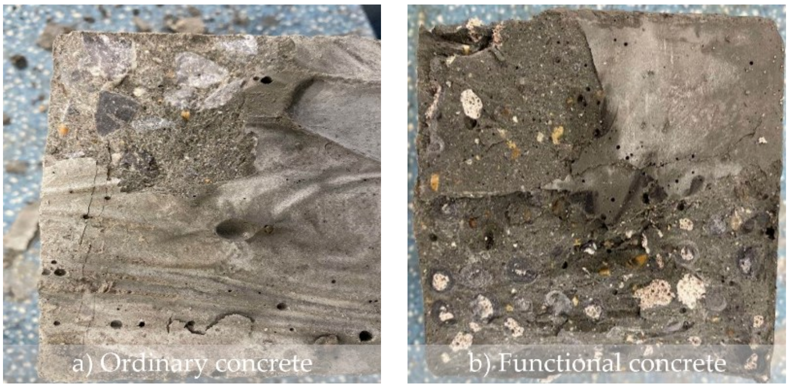

Figure 3 Fracture surfaces of the concrete samples

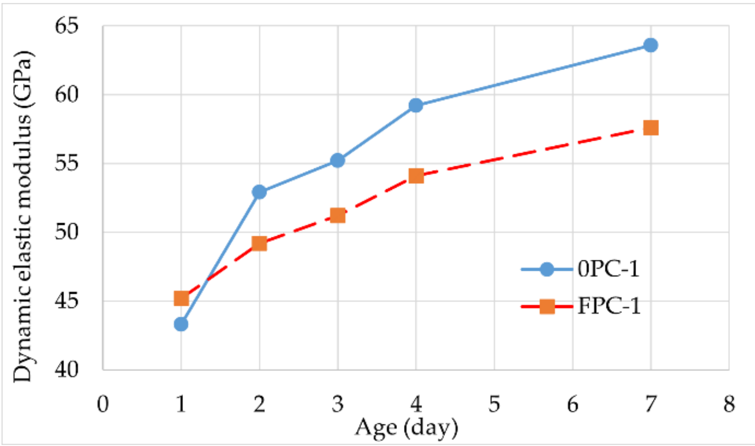

Figure 4 Dynamic elastic modulus of concrete at different ages

3.3.2 Dynamic Elastic Modulus

The dynamic elastic modulus of the two groups of concrete was tested, and the results at different ages are shown in Figure 4. The increase in the dynamic elastic modulus can be divided into two stages: a rapid increase from 0 to 14 days, followed by a slow increase after 14 days. This phenomenon occurs because as the concrete ages, the degree of hydration of the cement clinker minerals increases, leading to more gel formation and a reduction in capillary pores. The strength of the cement paste gradually increases, with tricalcium silicate, which plays a decisive role in the strength of clinker minerals, developing rapidly in the early stages. Thus, the strength of the cement increases rapidly from 3 to 14 days and then increases slowly after 28 days.

Table 14 Dynamic elastic modulus of the concrete (Unit: GPa)

Group	Age (day)					
	1-day	2-day	3-day	4-day	7-day	28-day
OPC-1	43.3	52.9	55.1	59.1	63.6	67.4
FPC-1	45.2	49.2	51.2	54.1	57.6	58.6

As shown in Table 14, the addition of functional aggregates reduces the elastic modulus of the concrete, and the trend of its modulus of elasticity growth is also relatively gentle. This is because the elastic modulus of functional aggregates is lower than that of ordinary aggregates, which results in a lower overall elastic modulus for the concrete. In ordinary concrete, the significant difference in the elastic modulus between coarse aggregates and mortar creates a composite of "hard" aggregates and "soft" mortar. Under alternating freeze-thaw or wet-dry conditions, the constraints imposed by coarse aggregates can generate high internal stresses, leading to microcracks or failure [10]. In contrast, functional aggregates have an elastic modulus closer to that of the surrounding mortar, creating a more homogeneous structure with "soft" aggregates and "hard" mortar. This "elastic coordination" reduces internal stresses and minimizes the risk of microcracking.

3.3.3 Chloride Ion Penetration Resistance of Concrete

The chloride ion penetration resistance of the two groups of samples was tested using the RCM method, and the results are shown in Table 15.

Table 15 Chloride ion penetration results at 28 days (Unit: 10^{-12} m²/s)

Group	Sample-1	Sample-2	Sample-3	Average
OPC	1.8	1.7	1.7	1.7
FPC	0.7	0.9	0.8	0.8

Table 15 shows that the addition of functional aggregates reduces the chloride ion penetration coefficient, indicating improved resistance to chloride ion erosion. This is because fly ash and functional aggregates form a unique rough surface, which enhances the bonding performance of the cement mortar and the strength of the cementitious materials on the surface of the functional aggregates [11]. This results in a dense structure in which the cement mortar tightly encapsulates the fly ash and functional aggregates, improving the compactness of the cement paste and preventing the formation of continuous water penetration channels, thereby increasing the impermeability of the concrete.

3.3.4 Microstructure of the Concrete

The microstructural morphology of the interfacial transition zone (ITZ) between the cement matrix and coarse aggregates in ordinary concrete (OPC) and functional concrete (FPC) was observed under different magnifications by scanning electron microscopy (SEM), as shown in Figures 5 and 6.

In ordinary concrete, the aggregate interface is relatively smooth, and large calcium hydroxide crystals are clearly visible in the ITZ at 5000× magnification. After a small amount of functional aggregates is added, the particle gradation of the concrete is improved. The SEM images at different magnifications clearly show that the porosity of functional concrete is significantly lower than that of ordinary concrete. The structure of the cement paste in the ITZ is denser, and the bonding between the cementitious materials and aggregates is tighter. At 2000× magnification, the ITZ of the functional concrete shows mechanical interlocking between the aggregates and the cement hydration products. However, unreacted spherical fly ash particles can still be observed in the cement paste near the aggregates. Unlike ordinary concrete, no large calcium hydroxide crystals are found at the interface, confirming that functional concrete is denser than ordinary concrete.

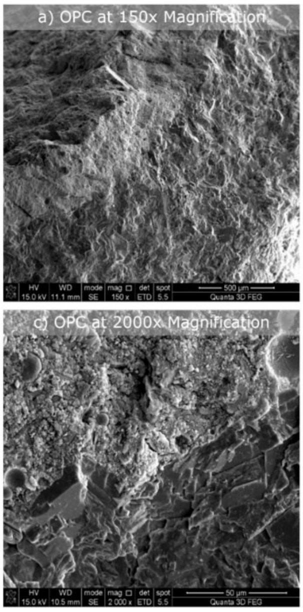

Figure 5 Microstructure of the ITZ in OPC

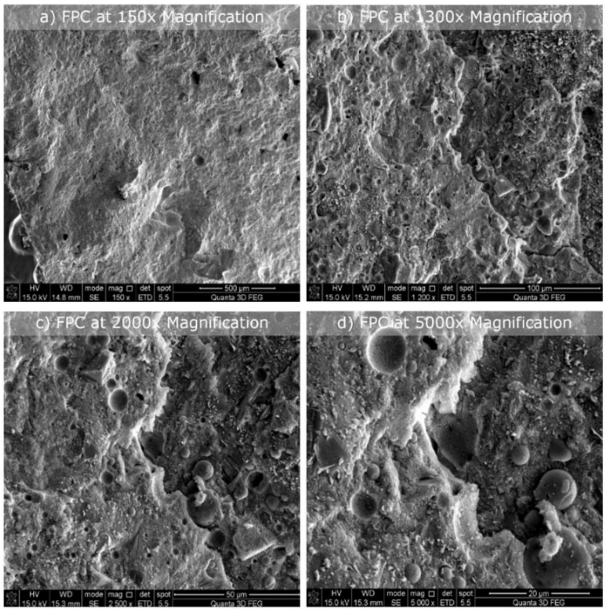

Figure 6 Microstructure of the ITZ in FPC

3.4 Influence of Functional Aggregates on Concrete Performance

On the basis of the above experiments, it was concluded that adding a small amount of functional aggregates significantly improved the workability of the concrete while also mitigating bleeding and bottom segregation. However, since functional aggregates have lower strength than coarse aggregates and are typically added in a saturated surface-dry state, they introduce additional water, increasing the W/B ratio and leading to a reduction in concrete strength. In practical engineering applications, the water content in the mix can be appropriately reduced to increase the concrete strength while maintaining the same workability.

Functional aggregates have a lower elastic modulus and strength, which limits their ability to restrain concrete deformation. However, the unique rough surface formed by functional aggregates and fly ash enhances the bonding performance of the cement mortar, making the concrete structure denser and improving its resistance to chloride ion penetration [12].

4 Multiobjective Mix Proportion Optimization and Performance Verification

4.1 Optimization of Concrete Mix Proportion

After several trial mix experiments, the preliminary mix proportion was determined. The selected parameters include a W/B ratio of 0.32, a water content of 150 kg, a cementitious material content of 460 kg, and a mineral admixture content of 40% (with a fly ash-to-slag powder ratio of 25:15). On the basis of the initial mix proportion, further optimization and adjustments were made. Functional coarse aggregates were used to replace 5–10 mm coarse aggregates by volume, and insulation functional aggregates were used to replace sand by volume. The optimized mix proportions are shown in Table 16.

Table 16 Optimized concrete mix proportions

Group	W/B	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
		Cement	Fly ash	Slag powder	Mass	Volume		
Baseline	0.32	60	25	15	40	42	/	1.30

Group	W/B	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
		Cement	Fly ash	Slag powder	Mass	Volume		
Low fly ash	0.32	65	15	20	40	45	/	1.30
Insulation aggregate	0.32	60	25	15	34	35	80	1.30
Functional aggregate	0.32	60	25	15	40	41	50	1.30

4.2 Concrete Performance Verification

4.2.1 Workability of Concrete

The workability of the concrete mixtures listed in Table 16 is shown in Table 17. After the two types of functional aggregates were added, the workability of the concrete improved. However, reducing the fly ash content led to a reduction in workability, with reductions in both slump and spread.

Table 17 Workability of concrete

Group	Slump (mm)	Spread (mm)	T50 (s)	Density (kg/m³)
Baseline	235	590	17	2,442
Low fly ash	220	540	19	2,440
Insulation aggregate	230	620	15	2,420
Functional aggregate	250	630	12	2,386

4.2.2 Mechanical Properties of Concrete

The mechanical properties of the concrete mixtures listed in Table 16 are shown in Table 18. The addition of functional aggregates resulted in a reduction in the strength of the concrete. However, since functional aggregates improve workability, the water content can be appropriately reduced in subsequent designs to reduce the water–binder ratio, thereby compensating for the strength loss caused by the addition of functional aggregates [13].

Table 18 Mechanical properties of the concrete (Units: MPa)

Group	Compressive strength		
	7-day	28-day	56-day
Baseline	51.3	76.5	82.3
Low fly ash	50.7	77.6	83.5
Insulation aggregate	42.7	72.3	81.6
Functional aggregate	45.5	71.2	74.5

4.2.3 Shrinkage Properties of Concrete

The drying shrinkage and autogenous shrinkage of the concrete mixtures listed in Table 16 were tested, and the results are shown in Tables 19 and 20. Figure 7 presents the drying shrinkage and autogenous shrinkage curves.

Table 19 Drying shrinkage of concrete (Unit: 10^{-6})

Group	Age (day)					
	1-day	2-day	3-day	4-day	5-day	7-day
Baseline	60	94	119	138	150	194
Low fly ash	63	99	136	169	188	221
Insulation aggregate	44	75	101	116	126	180

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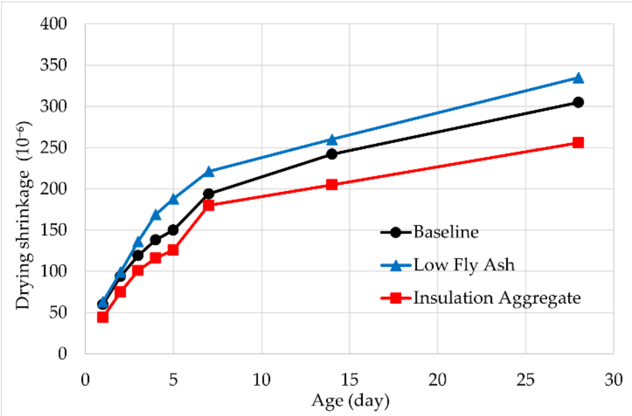
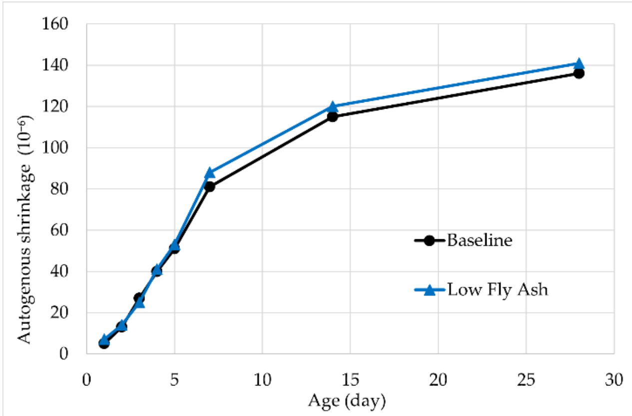
Table 20 Autogenous shrinkage of concrete (Unit: 10^{-6})

Group	Age (day)							
	1-day	2-day	3-day	4-day	5-day	7-day	14-day	28-day
Baseline	5	13	27	40	51	81	115	136
Low fly ash	7	14	25	41	53	88	120	141



a) Drying shrinkage (10^{-6})



b) Autogenous shrinkage (10^{-6})

Figure 7 Shrinkage curves of the concrete

Figure 7 a) shows that reducing the fly ash content increases both the drying shrinkage and autogenous shrinkage of the concrete. Compared with the baseline group, the drying shrinkage increased by 13.9% at 7 days and 10.2% at 28 days. This is because the pozzolanic reaction of fly ash (reacting with $Ca(OH)_2$ at later stages) results in the filling of pores and refines the pore structure, reducing the number of water evaporation channels. When the fly ash content is reduced, the pore structure becomes coarser, accelerating water loss and increasing drying shrinkage. As shown in Figure 7 b), the autogenous shrinkage of the low fly ash group increased by 8.6% at 7 days and 3.7% at 28 days compared with that of the baseline group. This is because reducing the fly ash content increases the relative cement content, accelerating the hydration reaction and generating more hydration products, which leads to increased autogenous shrinkage and may cause early microcracks.

Figure 7 a) shows that adding a small amount of insulation aggregates reduces the drying shrinkage of the concrete. Compared with the baseline group, the drying shrinkage decreased by 7.2% at 7 days and 16.1% at 28 days. This is because insulation aggregates can store water due to their porous nature, reducing water evaporation and providing long-term water retention. Additionally, the porous characteristics of insulation aggregates refine the internal pore structure of the concrete, increasing the tortuosity of water migration paths and reducing the rate of water evaporation, thereby significantly inhibiting drying shrinkage.

4.2.4 Thermal Properties of Concrete

Considering the temperature requirements for mass concrete, adiabatic temperature increase tests were conducted on three groups of concrete mixtures, as shown in Tables 21 and 22. The test results are presented in Figure 8 and Table 23.

Table 21 Mix proportion parameters

Group	W/B	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
		Cement	Fly ash	Slag powder	Mass	Volume		
Baseline	0.32	60	25	15	40	42	/	1.30

Group	W/B	Cementitious material ratio (%)			Sand ratio S_P (%)		Function aggregates (kg)	Water-reducing agent (%)
		Cement	Fly ash	Slag powder	Mass	Volume		
Insulation aggregate	0.32	60	25	15	34	35	80	1.30
Heat storage aggregate	0.32	60	25	15	40	41	50	1.30

Table 22 Concrete mix proportions (Unit: kg)

Group	W/B	Water	Cement	Fly ash	Slag powder	Sand	Coarse aggregate	Functional aggregates	Water-reducing agent
Baseline	0.32	150	272	118	70	736	1,104	/	5.96
Insulation aggregate	0.32	150	272	118	70	686	1,104	80	5.96
Heat storage aggregate	0.32	150	272	118	70	736	1,015	50	5.96

Table 23 Temperature increase data at 7 days (°C)

Group	Initial temperature	Final temperature	Maximum temperature increase
Baseline	/	/	46.17
Insulation aggregate	20.03	64.72	44.69
Heat storage aggregate	17.97	67.83	49.86

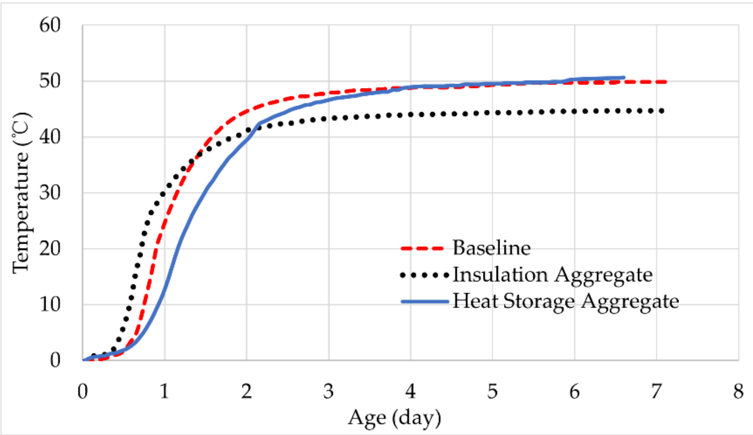


Figure 8 Curves of the temperature increase of concrete

Table 23 (Figure 8) shows that the incorporation of insulation aggregates delays the temperature increase in concrete. Compared with that of the baseline group, the maximum temperature increase in the group with insulation aggregates at 3 and 7 days decreased by approximately 1.5 °C. The group with heat storage aggregates, in which paraffin was incorporated directly into the concrete, exhibited significant temperature control effects in the first 2 days, effectively slowing the rate of temperature increase.

4.3 Conclusions from the Optimization Tests

After performance testing and optimization of the initially determined concrete mix proportion, the concrete achieved a slump of 235 mm, a spread of 590 mm, and a 28-day compressive strength of 76.5 MPa, meeting the requirements for high strength and high fluidity. After functional aggregates of equal volume were added, the concrete workability was significantly improved without a noticeable reduction in strength, still satisfying the C55 strength requirement. In practical projects, the water content can be appropriately reduced to increase the concrete strength while maintaining the same workability [14].

When insulation aggregates were added, the temperature increase in the concrete was delayed, and the peak temperature slightly decreased. When heat storage aggregates were added, the temperature control effects were obvious in the first two days after pouring, effectively slowing the rate of temperature increase.

The final mix proportions for C55 high-fluidity pumped mass concrete are as follows: a W/B ratio of 0.32, a water content of 150 kg, a cementitious material content of 460 kg, and a mineral admixture content of 40% (with a fly ash–slag powder ratio of 25:15). Functional coarse aggregates (50 kg) were used to replace 5–10 mm coarse aggregates by volume, and insulation functional aggregates (30 kg) were used to replace sand by volume. The proportions of the constituents of the concrete are shown in Table 24.

Table 24 Concrete mix proportions (Unit: kg)

Category	W/B	Water	Cement	Fly ash	Slag powder	Sand	Coarse aggregate	Functional aggregates	Insulation aggregates	Water-reducing agent
Quantity	0.32	150	272	118	70	686	1,074	50	30	5.96

5 Conclusions

For the pylon concrete, multistage mix proportion design and optimization was conducted through more than 20 trial mix experiments. The influences of parameters such as the cementitious material content, mineral admixture ratio, sand ratio, and presence of functional aggregates on the workability of concrete were studied, and the preliminary mix proportions were determined. The effects of cement type and functional aggregates on concrete performance were explored, and the mix proportion was further optimized on the basis of these findings. Finally, after performance testing and optimization of the initially determined mix proportion, the concrete met the multiobjective performance requirements for pylon concrete, enhancing the safety and durability of the project. The following conclusions can be drawn from this study.

(1) Systematic design and optimization: The design of high-strength, high-fluidity, and high-pumpability mass concrete is a critical systematic task. Given the numerous factors affecting concrete performance, multistage design optimization and performance verification are essential. The key steps include raw material selection, preliminary mix proportion parameter determination, mix proportion optimization, exploration of factors influencing concrete performance, reoptimization of the mix proportion, performance verification, and final mix proportion determination.

(2) Cementitious material and mineral admixture ratios: To meet the requirements of high strength, high fluidity, and low heat of hydration, the cementitious material content should be within the range of 456–500 kg/m^3, preferably at the lower end. The ratio of fly ash-to-slag powder significantly affects workability, and the total mineral admixture content should be within 40% ± 5% (with a fly ash-to-slag powder ratio of 25:15). Increasing the fly ash content improves fluidity while maintaining the total admixture content.

(3) Sand ratio and functional aggregates: As the sand ratio increases, the slump and spread of concrete improve, but the slump retention worsens. Adding functional aggregates significantly enhances the workability and reduces bleeding and bottom segregation. For high-strength, high-fluidity, and high-pumpability mass concrete, the sand ratio is recommended to be within 40–45%, preferably at the lower end.

(4) Functional aggregates and temperature control: Adding functional aggregates of equal volume improves workability without compromising strength. In

practical applications, reducing the water content while maintaining workability can increase concrete strength. Insulation aggregates delay the temperature increase in the concrete and slightly reduce the peak temperature. Heat storage aggregates significantly slow the rate of increase in temperature during the first two days after the concrete is poured.

Conflict of interest: All the authors disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Zhu, upon reasonable request.

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AUTHOR BIOGRAPHIES

	**Xiaoliang Zhu** B.E., Senior Engineer. Graduated from Nanchang University in 2013. Research Direction: Large Span Bridge Construction. Email: 1147263435@qq.com		**Baoan Quan** Engineer. Graduated from Xi'an Railway Engineering Workers' University in 2013. Research Direction: Large Span Bridge Construction. Email: 185293585@qq.com

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<table>
<tr>
<td></td>
<td>Sheng Fang
B.E., Assistant Engineer. Graduated from Suzhou University in 2020.
Research Direction: Large Span Bridge Construction.
Email: 3054159847@qq.com</td>
<td></td>
<td>Hao Wei
B.E., Assistant Engineer. Graduated from Zhengzhou University of Aeronautics in 2020.
Research Direction: Large Span Bridge Construction.
Email: 915715663@qq.com</td>
</tr>
<tr>
<td></td>
<td>Junchen Zhao
B.E., Assistant Engineer. Graduated from Wuhan University of Engineering Science in 2022.
Research Direction: Large Span Bridge Construction.
Email: 2627000659@qq.com</td>
<td></td>
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