

Study on the Workability and Mechanical Properties of Low-Carbon Fair-Faced Concrete Incorporating Multiple Mineral Admixtures

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Abstract

To achieve coordinated optimization of workability and mechanical performance in fair-faced concrete, an ordinary Portland cement-based binder system incorporating fly ash (FA), ground granulated blast-furnace slag (BFS), metakaolin (MK), and diatomite (DE) was developed to prepare low-carbon fair-faced concrete with multiple mineral admixtures. An $L_{16}(4^4)$ orthogonal design was employed to systematically investigate the effects of these factors on spread diameter, T_{500} , compressive strength at 3, 7, and 28 days, and splitting tensile strength at the same ages. Range analysis, analysis of variance, interaction analysis, and the entropy weight-TOPSIS method were further used for comprehensive evaluation. The results show that workability is mainly governed by FA and MK: FA improves flowability, whereas MK and DE increase system cohesiveness and impair fresh-state performance. The strength at all ages is dominated by BFS, indicating that slag powder is the key constituent for enhancing the mechanical properties of low-carbon fair-faced concrete. Comprehensive evaluation ranked the 16 mixtures in the order of L7, L8, and L4, with L7 exhibiting the best overall performance. The study demonstrates a clear need to balance workability and strength in systems containing multiple mineral admixtures, and that the synergistic use of moderate FA and relatively high BFS is more conducive to improving the overall performance of low-carbon fair-faced concrete.

Keywords

Low-carbon Fair-faced Concrete; Mineral Admixtures; Workability; Mechanical Properties; Orthogonal Experiment.

1. Introduction

Fair-faced concrete is a high-quality concrete that combines structural load-bearing capacity with architectural appearance. Owing to its natural surface, authentic texture, and the elimination of secondary finishing, it has been increasingly used in public buildings, municipal landscapes, cultural buildings, and prefabricated components [1–3]. Compared with ordinary concrete, fair-faced concrete requires not only adequate workability and mechanical performance, but also sufficient flowability and cohesiveness of the fresh mixture to ensure uniform surface color, fewer pore defects, and stable overall appearance after casting [4]. Therefore, material design and mix optimization remain key issues in fair-faced concrete research.

With the continued advancement of the dual-carbon strategy and the growing demand for green and low-carbon transformation in building materials, the partial replacement of cement with mineral admixtures has become an important route for reducing the carbon emissions of concrete [5]. Fly ash, slag powder, metakaolin, and diatomite can not only reduce clinker consumption, but also affect workability and mechanical performance by improving particle

packing, regulating rheological behavior, and optimizing the microstructure. However, because these admixtures differ substantially in activity level, particle morphology, and water demand, the effects of multi-component blending are not simply additive and may exhibit either synergistic or antagonistic behavior [6]. In fair-faced concrete, such coupling affects not only strength development but also construction adaptability and the final casting quality [7].

At present, most studies on the influence of mineral admixtures on fair-faced concrete focus on single or limited components, and there is still a lack of systematic parametric design and quantitative analysis for composite systems composed of fly ash, slag powder, metakaolin, and diatomite [8]. Especially under low water-to-binder ratios, multi-admixture systems can significantly alter paste viscosity, particle packing, and early hydration, thereby affecting spread diameter, T_{500} , and strength development at different ages [9]. Without systematic investigation, practical applications may suffer from insufficient flowability, inadequate strength reserve, or difficulty in balancing the two. It is therefore necessary to systematically analyze the effects of multiple mineral admixtures on the workability and mechanical properties of low-carbon fair-faced concrete by means of orthogonal testing, to identify the main controlling factors and their interactions, and to screen representative optimal mix proportions.

Accordingly, this study used ordinary Portland cement as the matrix binder and selected fly ash, slag powder, metakaolin, and diatomite as mineral admixtures. A four-factor, four-level orthogonal design was adopted to investigate the effects of individual factors and their combinations on the workability and mechanical properties of low-carbon fair-faced concrete, with spread diameter, T_{500} , compressive strength, and splitting tensile strength as the main response indices. Range analysis, analysis of variance, interaction analysis, and multi-index comprehensive optimization were then conducted to identify typical mixtures with superior overall performance, thereby providing a basis for mix design and subsequent studies on low-carbon fair-faced concrete.

2. Materials and Methods

2.1. Materials

Table 1. Chemical composition of cement (%)

Component	CaO	SiO ₂	Al ₂ O ₃	SO ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	TiO ₂
Content	62.55	21.89	5.58	2.89	2.86	2.26	0.87	0.83	0.19

Table 2. Performance indexes of cement

Specific surface area(m ² ·kg ⁻¹)	Setting time / min		Flexural strength / MPa		Compressive strength / MPa	
	Initial set	Final set	3d	28d	3d	28d
336	178	228	5.1	8.1	25.0	46.2

Ordinary Portland cement (P·O 42.5, OPC) was used as the primary binder in this study. Fly ash (FA), ground granulated blast-furnace slag (BFS), metakaolin (MK), and diatomite (DE) were incorporated to prepare low-carbon fair-faced concrete. The OPC was supplied by Hunan Pingtang Southern Cement Co., Ltd. The FA was Grade I fly ash, the BFS was S95-grade ground granulated blast-furnace slag, the MK was highly reactive metakaolin, and the DE was calcined 200-mesh diatomite. Their basic properties are listed in Tables 1–6. A 540P polycarboxylate high-range water reducer with a water-reduction rate of 30% was used. Tap water was used for mixing. The fine aggregate was Zone II medium sand with a fineness modulus of 2.7 and an

apparent density of 2610 kg/m³, while the coarse aggregate was continuously graded crushed stone with a particle size of 5–20 mm and an apparent density of 2700 kg/m³.

Table 3. Physical properties of FA

No.	Test item	Specification			Measured value
		Grade I	Grade II	Grade III	
1	Fineness (45 μm residue), %	≤12.0	≤30.0	≤45.0	11.2
2	Water demand ratio, %	≤95	≤105	≤115	92
3	Loss on ignition, %	≤5.0	≤8.0	≤10.0	4.28
4	Free CaO content	≤1.0% (Class F fly ash)			0.64

Table 4. Physical properties of GGBS

Density (g/cm ³)	Specific surface area (m ² /kg)	Initial setting time ratio (%)	Fluidity ratio (%)	7-day activity index (%)	28-day activity index (%)
2.87	436	148	100	88	97

Table 5. Physical properties of MK

Density (g/cm ³)	Specific surface area (m ² /g)	Moisture content (%)	Water demand ratio (%)	7-day activity index (%)	28-day activity index (%)
2.60	16.0	0.8	112	110	128

Table 6. Performance index of DE

SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	Loss on ignition	Bulk density	Moisture content
85.00%	1.30%	3.35%	2.00%	0.36 g/cm ³	1.90%

2.2. Experimental Design and Mix Proportions

Table 7. Mix Ratios of Each Test Group (g/m³)

Group	Water	OPC	FA	BFS	MK	DE	Sand	Crushed stone	Water reducer
L1	154	480.0	0.0	0.0	0.0	0.0	712	1088	4.8
L2	154	393.6	0.0	48.0	19.2	19.2	712	1088	4.8
L3	154	307.2	0.0	96.0	38.4	38.4	712	1088	4.8
L4	154	220.8	0.0	144.0	57.6	57.6	712	1088	4.8
L5	154	374.4	48.0	0.0	19.2	38.4	712	1088	4.8
L6	154	326.4	48.0	48.0	0.0	57.6	712	1088	4.8
L7	154	278.4	48.0	96.0	57.6	0.0	712	1088	4.8
L8	154	230.4	48.0	144.0	38.4	19.2	712	1088	4.8
L9	154	288.0	96.0	0.0	38.4	57.6	712	1088	4.8
L10	154	240.0	96.0	48.0	57.6	38.4	712	1088	4.8
L11	154	268.8	96.0	96.0	0.0	19.2	712	1088	4.8
L12	154	220.8	96.0	144.0	19.2	0.0	712	1088	4.8
L13	154	259.2	144.0	0.0	57.6	19.2	712	1088	4.8
L14	154	249.6	144.0	48.0	38.4	0.0	712	1088	4.8
L15	154	163.2	144.0	96.0	19.2	57.6	712	1088	4.8
L16	154	153.6	144.0	144.0	0.0	38.4	712	1088	4.8

To achieve coordinated optimization of strength, appearance, and carbon-reduction performance in low-carbon fair-faced concrete, a four-factor, four-level orthogonal design was adopted. FA, BFS, MK, and DE contents were taken as control factors to investigate the effects

of the multi-mineral admixture system on workability, mechanical performance, appearance quality, and carbon emissions. The factor levels were set as follows: FA = 0%, 10%, 20%, and 30%; BFS = 0%, 10%, 20%, and 30%; MK = 0%, 4%, 8%, and 12%; and DE = 0%, 4%, 8%, and 12%. In the mix design, the total binder content was fixed at 480 kg/m³, the water-to-binder ratio was 0.32, the sand ratio was 40%, and the mixing water content was 154 kg/m³. The aggregate contents were determined by the absolute-volume method and kept essentially constant for all groups. One control group and 16 orthogonal test groups were designed. The detailed mix proportions are given in Table 7.

2.3. Specimen Preparation

Cube specimens with dimensions of 150 mm × 150 mm × 150 mm were prepared. At least three parallel specimens were produced for each group and each age for the tests of workability, compressive strength, splitting tensile strength, and appearance. One face of each specimen was reserved as the fair-faced surface and was not subjected to secondary troweling. The concrete was mixed using a forced horizontal-shaft mixer. The coarse and fine aggregates were first dry-mixed, followed by the addition of the binder materials until the mixture was uniform. Water and water reducer were then added in two steps and mixing continued until a homogeneous mixture free of segregation was obtained. The concrete was cast in layers and compacted in the molds. After casting, the specimens were covered for curing, demolded after 24 h, and then cured under standard conditions at 20 ± 2 °C and relative humidity not lower than 95% until the specified ages.

2.4. Test Methods

Workability was evaluated by spread-diameter testing, with spread diameter and T_{500} used to characterize the flowability and cohesiveness of the fresh mixture. The tests were conducted in accordance with “Standard for test method of performance on ordinary fresh concrete (GB/T 50080-2016)”. Mechanical performance was evaluated by compressive strength and splitting tensile strength tests in accordance with “Standard for test methods of concrete physical and mechanical properties (GB/T 50081-2019)”. The average value of three parallel specimens was taken as the test result for each group.

3. Results and Discussion

3.1. Range Analysis

Based on the above orthogonal design, 16 combinations of low-carbon fair-faced concrete were prepared, and their workability and mechanical properties were tested in accordance with the relevant standards. The test results are presented in Table 8.

To clarify the effects of FA, BFS, MK, and DE contents on the workability and mechanical properties of low-carbon fair-faced concrete, range analysis was performed on the spread diameter, T_{500} , compressive strength at different ages, and splitting tensile strength at different ages based on the $L_{16}(4^4)$ orthogonal test results. The range value R was used to characterize the degree of influence of each factor. The results for each index are shown in Table 9 and Fig. 1–3.

In terms of workability, the order of influence on spread diameter was MK > FA > DE > BFS. MK had the most pronounced effect: as its content increased, the spread diameter decreased overall, indicating that metakaolin increased paste cohesiveness and water demand, thereby weakening flowability. FA ranked second, and its increase generally enhanced the spread diameter, showing that fly ash improved workability through ball-bearing and filling effects. DE also reduced the spread diameter, mainly owing to its porous and water-absorbing characteristics, whereas BFS had the weakest influence. For T_{500} , the order of influence was FA > MK > DE > BFS. FA and MK were the most sensitive factors affecting flow rate. Increasing FA

reduced T500, indicating a lower flow resistance, whereas increasing MK significantly increased T500, showing that metakaolin increased paste viscosity and retarded flow. DE also showed a delaying effect, while BFS had the least effect. Overall, FA mainly improved flowability, whereas MK and DE tended to increase paste cohesiveness and impair workability.

Table 8. Test results of the working performance and mechanical properties of low-carbon clear concrete

Group	FA%	BFS%	MK%	DE/%	Spread diameter / mm	T ₅₀₀ /s	Compressive strength / MPa			Splitting tensile strength / MPa		
							3d	7d	28d	3d	7d	28d
L1	0	0	0	0	571	3.3	34.2	45.3	57.8	2.93	2.71	4.33
L2	0	10	4	4	557	3.3	34.2	43.2	56.9	2.88	3.56	4.18
L3	0	20	8	8	540	4.0	34.3	44.5	56.9	2.96	3.69	4.21
L4	0	30	12	12	511	4.1	34.8	45.2	61.1	3.07	3.82	4.61
L5	10	0	4	8	561	3.3	33.4	42.9	52.4	2.79	3.43	3.94
L6	10	10	0	12	566	3.5	32.8	40.7	54.1	2.76	3.28	4.06
L7	10	20	12	0	543	3.4	34.1	47.4	62.0	3.01	3.97	4.72
L8	10	30	8	4	546	3.8	35.0	45.8	61.8	3.12	3.89	4.58
L9	20	0	8	12	557	3.6	32.6	41.6	51.1	2.71	3.32	3.88
L10	20	10	12	8	541	3.5	32.2	41.0	52.2	2.73	3.26	3.97
L11	20	20	0	4	568	3.2	33.0	46.4	60.0	2.85	3.78	4.39
L12	20	30	4	0	571	3.3	33.5	44.1	57.0	2.89	3.55	4.14
L13	30	0	12	4	563	3.5	32.6	41.3	53.4	2.74	3.29	4.03
L14	30	10	8	0	583	3.3	31.8	39.7	51.1	2.66	3.11	3.82
L15	30	20	4	12	557	3.2	33.7	43.4	55.0	2.91	3.47	4.17
L16	30	30	0	8	576	3.1	34.1	43.1	55.3	2.98	3.44	4.24

Table 9. Results of Extreme Difference Analysis

Index	Range value					
	FA	BFS	MK	DE	Order of influence	Optimal level
Spread diameter	25.0	12.0	30.75	19.25	MK>FA>DE>BFS	A4B1C1D1
T ₅₀₀	0.4	0.175	0.4	0.275	FA>MK>DE>BFS	A4B2C1D1
3-day compressive strength	1.55	1.6	0.275	0.3	BFS>FA>DE>MK	A1B4C2D2
7-day compressive strength	2.675	4.275	0.975	1.45	BFS>FA>DE>MK	A1B3C1D2
28-day compressive strength	4.475	5.225	1.95	3.825	BFS>FA>DE>MK	A1B4C4D2
3-day splitting tensile strength	0.165	0.258	0.025	0.035	BFS>FA>DE>MK	A1B4C4D2
7-day splitting tensile strength	0.315	0.54	0.283	0.295	BFS>FA>DE>MK	A2B3C4D2
28-day splitting tensile strength	0.268	0.385	0.225	0.205	BFS>FA>MK>DE	A1B4C4D2

For mechanical performance, the order of influence on compressive strength at 3, 7, and 28 days was generally BFS > FA > DE > MK. At 3 days, BFS and FA were the most influential factors: the former improved early strength with increasing dosage, while the latter slightly reduced strength because of dilution of the effective early cementitious phase. MK and DE had relatively weak main effects. At 7 and 28 days, the dominant role of BFS became more pronounced, indicating that slag powder promoted the formation of gel products through micro-filling and later pozzolanic/hydraulic reactions and was therefore the key factor controlling medium- and

long-term strength development. Although FA was beneficial to workability, compressive strength generally decreased as its dosage increased. DE was beneficial to particle packing and microstructural refinement at low dosages and thus promoted medium- and late-age strength to some extent, whereas MK had the weakest influence overall.

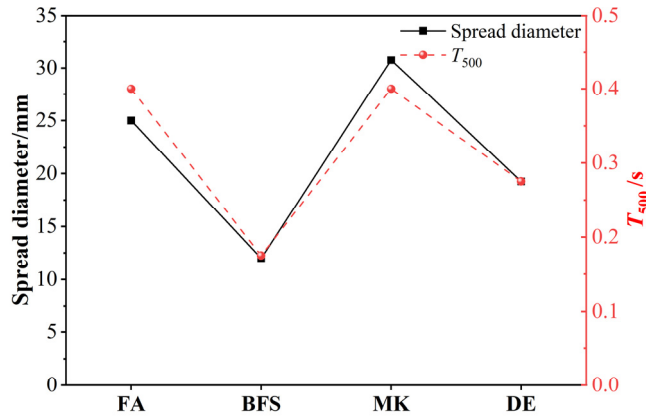


Fig 1. Range analysis of spread diameter and T_{500}

The variation in splitting tensile strength was generally consistent with that of compressive strength, with BFS remaining the dominant factor at all ages. BFS had the most pronounced effect on improving early crack resistance and medium- to late-age tensile performance. Increasing FA generally reduced splitting tensile strength. The effects of DE and MK became somewhat more evident at 7 and 28 days, indicating that both contributed positively to the optimization of the interfacial transition zone and to improved later-age crack resistance.

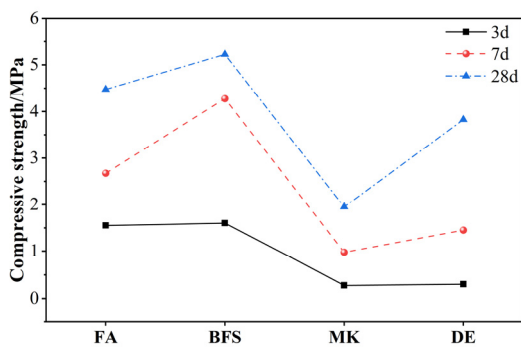


Fig 2. Range analysis of compressive strength

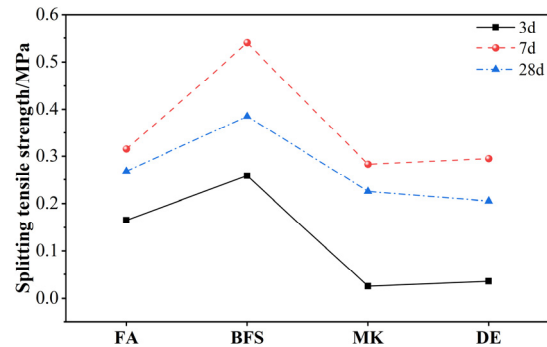


Fig 3. Range analysis of splitting tensile strength

Overall, FA mainly improved workability but was unfavorable to medium- and late-age strength; BFS was the dominant factor for enhancing compressive and tensile strength; MK significantly impaired workability but provided some benefit to later-age tensile performance; and DE showed a dual effect, being unfavorable to workability but beneficial to medium- and late-age strength. These results indicate that mix-proportion optimization should seek coordinated performance among FA, BFS, MK, and DE.

3.2. Analysis of Variance and Significance

Range analysis can only provide a preliminary ranking of factor importance and cannot reflect statistical significance. Therefore, analysis of variance (ANOVA) was further conducted for each index, and the effects of FA, BFS, MK, and DE were evaluated in terms of F value, p value, and contribution ratio. Because this study employed a single-run $L_{16}(4^4)$ orthogonal design without

replicated groups, the residual term was used as the estimate of experimental error for significance testing. The results are shown in Table 10 and Fig. 4–11.

Table 10. Results of Variance Analysis and Significance Test

Index	ANOVA summary
Spread diameter	MK (43.1%, $p = 0.015$, significant); FA (28.0%, $p = 0.028$, significant); DE (16.7%, $p = 0.056$, marginally significant); BFS (10.3%, $p = 0.103$, not significant)
T_{500}	MK (45.9%, $p = 0.097$, marginally significant); FA (27.7%, $p = 0.174$, not significant); DE (12.3%, $p = 0.376$, not significant); BFS (5.9%, $p = 0.609$, not significant)
3-day compressive strength	FA (46.1%, $p = 0.081$, marginally significant); BFS (43.7%, $p = 0.087$, marginally significant); MK (1.5%, $p = 0.883$, not significant); DE (1.5%, $p = 0.887$, not significant)
7-day compressive strength	BFS (58.7%, $p = 0.039$, significant); FA (23.1%, $p = 0.127$, not significant); DE (9.9%, $p = 0.306$, not significant); MK (3.0%, $p = 0.669$, not significant)
28-day compressive strength	BFS (49.3%, $p = 0.012$, significant); FA (26.0%, $p = 0.030$, significant); DE (17.0%, $p = 0.053$, marginally significant); MK (5.9%, $p = 0.189$, not significant)
3-day splitting tensile strength	BFS (63.8%, $p = 0.056$, marginally significant); FA (27.0%, $p = 0.161$, not significant); DE (1.1%, $p = 0.923$, not significant); MK (0.6%, $p = 0.968$, not significant)
7-day splitting tensile strength	BFS (55.7%, $p = 0.081$, marginally significant); FA (13.1%, $p = 0.374$, not significant); DE (11.3%, $p = 0.418$, not significant); MK (11.2%, $p = 0.422$, not significant)
28-day splitting tensile strength	BFS (48.3%, $p = 0.056$, marginally significant); FA (23.6%, $p = 0.137$, not significant); MK (13.3%, $p = 0.253$, not significant); DE (9.2%, $p = 0.353$, not significant)

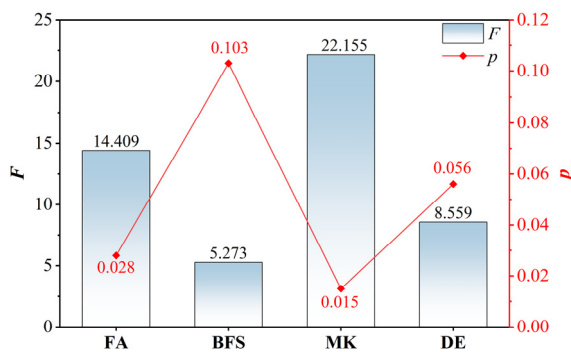


Fig 4. ANOVA results for spread diameter

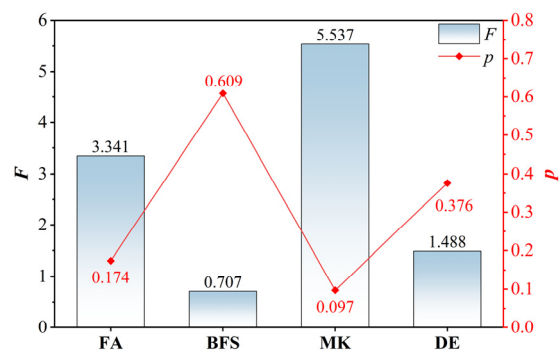


Fig 5. ANOVA results for T_{500}

The ANOVA results indicate that workability was mainly controlled by MK and FA. For spread diameter, both MK and FA reached significance, with contribution ratios of 43.11% and 28.03%,

respectively, indicating that MK was the primary factor suppressing the spread diameter, whereas FA improved flowability. DE was marginally significant, while BFS had the weakest effect. For T500, MK had the highest contribution ratio (45.86%) and was marginally significant, indicating that it was the most sensitive factor affecting paste viscosity and flow rate. FA, DE, and BFS did not reach significance. Overall, MK had the strongest control over workability, FA mainly improved overall flowability, and BFS had a relatively weak direct effect on fresh performance.

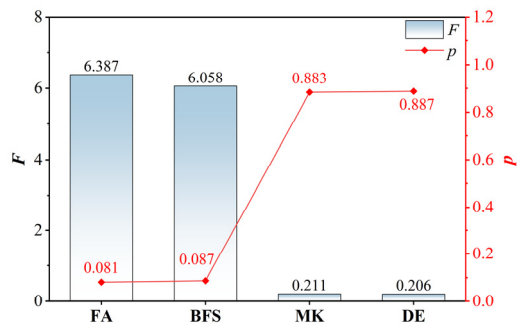


Fig 6. ANOVA results for 3-day compressive strength

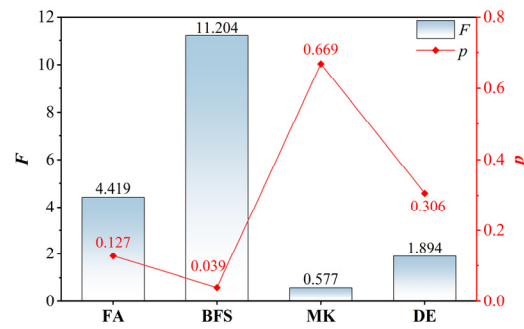


Fig 7. ANOVA results for 7-day compressive strength

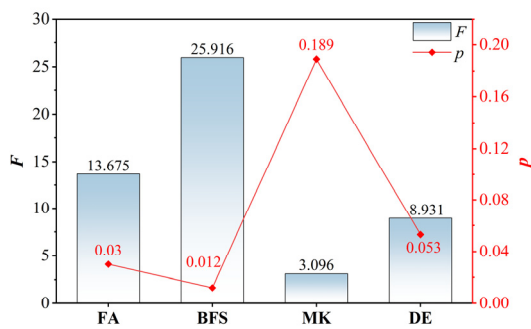


Fig 8. ANOVA results for 28-day compressive strength

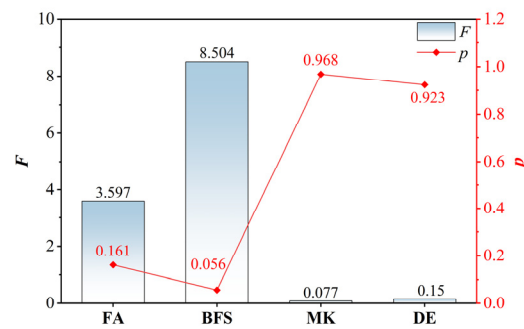


Fig 9. ANOVA results for 3-day splitting tensile strength

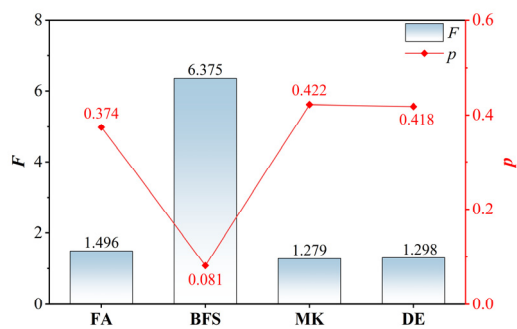


Fig 10. ANOVA results for 7-day splitting tensile strength

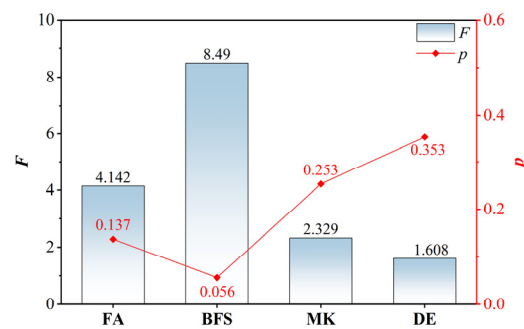


Fig 11. ANOVA results for 28-day splitting tensile strength

The influence on compressive strength changed with age, evolving from the combined action of FA and BFS at early age to BFS-dominant control at later ages. At 3 days, both FA and BFS were marginally significant and were the main factors governing early strength. FA mainly showed a dilution effect, whereas BFS promoted early strength through micro-filling and activity activation. At 7 and 28 days, the contribution ratio and significance of BFS increased further, making it the decisive factor controlling medium- and late-age compressive strength. FA still

had a significant effect at 28 days, but mainly in a negative way at high dosages. DE showed a marginally significant contribution to 28-day compressive strength, whereas MK had a relatively weak effect.

The pattern for splitting tensile strength was generally consistent with that for compressive strength, but the dominant role of BFS was even more pronounced. At 3, 7, and 28 days, BFS consistently had the highest contribution ratio and reached marginal significance, whereas FA, MK, and DE were generally not significant. This indicates that slag powder most effectively optimized the interfacial structure and restrained crack propagation, and is therefore the key constituent for improving tensile and cracking resistance.

The above ANOVA results show that workability was mainly controlled by MK and FA, with MK being the most sensitive factor affecting spread diameter and T_{500} and the key factor influencing paste cohesiveness and flow resistance, while FA mainly improved workability. Mechanical performance, by contrast, was dominated by BFS, especially with respect to 7-day and 28-day compressive strength and splitting tensile strength at all ages. FA exhibited a dual effect on strength, DE promoted later-age compressive strength to some extent, and MK was more suitable as a workability-regulating constituent.

3.3. Analysis of Interaction Trends

Range analysis and ANOVA primarily reveal the main effects of individual factors, whereas the various constituents in a multi-mineral admixture system may also exhibit synergistic or antagonistic interactions. It is therefore necessary to further analyze the pairwise interactions among FA, BFS, MK, and DE with respect to workability and mechanical performance. Because this study used a single-run orthogonal design without dedicated interaction columns or replicated groups, the present analysis is intended mainly to reveal interaction trends and their engineering implications. The results are listed in Table 11.

Table 11. Results of Main Interaction Screening

Index	Interaction term	Interaction type	<i>p</i> value
7-day compressive strength	FA×BFS	Negative interaction	0.042
7-day compressive strength	FA×MK	Negative interaction	0.040
7-day compressive strength	FA×DE	Positive interaction	0.012
28-day compressive strength	FA×BFS	Negative interaction	0.022
28-day compressive strength	FA×DE	Positive interaction	0.016
3-day splitting tensile strength	FA×DE	Positive interaction	0.046
7-day splitting tensile strength	FA×BFS	Negative interaction	0.044
7-day splitting tensile strength	FA×MK	Negative interaction	0.045
7-day splitting tensile strength	FA×DE	Positive interaction	0.098
28-day splitting tensile strength	FA×BFS	Negative interaction	0.079
28-day splitting tensile strength	FA×DE	Positive interaction	0.030

Interaction analysis showed that workability was generally insensitive to two-factor interactions, and the variations in spread diameter and T_{500} were still mainly governed by main effects. FA consistently improved workability by increasing spread diameter and reducing T_{500} , whereas MK and DE increased paste cohesiveness, reduced the spread range, and prolonged flow time. Although different factor combinations caused some fluctuation, no particularly prominent significant interaction terms were observed. This suggests that, within the range of this study, the variation in workability was primarily the superposition of particle morphology, water demand, and paste-viscosity effects of the admixtures, rather than the result of strong coupling.

Compared with workability, mechanical performance—especially the strengths at 7 and 28 days—was more sensitive to interactions, which were mainly associated with FA. FA×DE showed a relatively stable positive interaction in 7-day and 28-day compressive strength as well as in splitting tensile strength at some ages, indicating that an appropriate combination of DE and FA improved particle packing and the matrix structure, thereby promoting strength development at medium and later ages. In contrast, FA×BFS mainly showed a negative interaction in medium- and late-age compressive and splitting tensile strength, indicating that when FA and BFS were both present at relatively high dosages, their strength contributions could not simply be superimposed and might even suppress strength development because of reduced clinker proportion and competition in reactive processes. FA×MK also showed a negative interaction in some medium-age strength indices, indicating that simultaneous increases in FA and MK were unfavorable to matrix formation at this stage. By contrast, the interactions of BFS×MK, BFS×DE, and MK×DE were generally weak and mostly behaved as main-effect superposition. Overall, FA was the factor most likely to interact with other admixtures: FA×DE was a beneficial combination, whereas FA×BFS and FA×MK were unfavorable. In engineering applications, BFS should therefore be used as the main strengthening constituent, supplemented by an appropriate amount of DE, while FA should be controlled within a reasonable range and MK should be used at low or moderate dosages.

3.4. Comprehensive Optimization of Workability–Strength Mix Proportions

Based on the orthogonal test results, the effects of FA, BFS, MK, and DE on the workability and mechanical performance of low-carbon fair-faced concrete were systematically analyzed by range analysis, ANOVA with significance testing, interaction analysis, and multi-index comprehensive optimization. The results showed that FA mainly improved spread diameter and T500 and was therefore an important constituent for enhancing flowability; MK was the most sensitive factor affecting workability, and increasing its dosage significantly increased system cohesiveness and impaired flow behavior; BFS exhibited the strongest dominant effect on 7-day and 28-day compressive strength and on splitting tensile strength at all ages, and was thus the key factor governing mechanical performance; and DE displayed a dual effect, being unfavorable to workability but beneficial to medium- and late-age strength. Interaction analysis further showed a certain positive synergy between FA and DE and antagonistic relations between FA and BFS as well as between FA and MK in later-age strength development.

On this basis, the entropy weight-TOPSIS method was used for the comprehensive evaluation of workability and strength. The results showed that among the 16 orthogonal mixtures, L7, L8, and L4 ranked highest in overall performance. L7 achieved the best overall performance, maintaining workability adequate for construction while also exhibiting relatively high 7-day and 28-day compressive strength and splitting tensile strength. L8 showed an advantage in early compressive and splitting tensile performance, whereas L4 also demonstrated good application potential by balancing a certain level of workability with medium- and late-age mechanical performance.

Further main-effect analysis of the comprehensive score yielded a theoretical optimum factor combination of FA 0%, BFS 30%, MK 0%, and DE 4%. This combination reflects an overall design tendency in which BFS acts as the main strengthening constituent and DE serves as an auxiliary optimizing constituent. However, because both FA and MK are absent, this theoretical optimum does not reflect the research objective of composite design using multiple mineral admixtures and was therefore not selected as the focus of subsequent analysis.

Considering representativeness, data support, and continuity of the subsequent study, four mix proportions—L1, L4, L7, and L8—were finally selected for further investigation. L1 served as the control group, whereas L7, L8, and L4 represented typical low-carbon mixtures with the

best overall performance, better early-age performance, and well-balanced properties, respectively.

4. Conclusion

(1) Multiple mineral admixtures exerted distinctly different effects on the workability and mechanical performance of low-carbon fair-faced concrete. Workability was mainly controlled by FA and MK: FA improved the flowability of the fresh mixture, whereas MK and DE increased system cohesiveness and impaired workability. The compressive and splitting tensile strengths at all ages were dominated by BFS.

(2) ANOVA and interaction analysis showed that MK was the key factor affecting workability, whereas BFS was the core constituent for strength enhancement. FA and DE showed a certain positive synergy, while FA×BFS and FA×MK exhibited negative interactions in some medium- and late-age strength indices.

(3) Based on the entropy weight-TOPSIS evaluation, the mixtures ranked highest in comprehensive performance were L7, L8, and L4, among which L7 achieved the best balance between workability and mechanical performance. The theoretical optimum combination was FA 0%, BFS 30%, MK 0%, and DE 4%, but it was not selected as the focus of subsequent analysis.

(4) In summary, mix design for low-carbon fair-faced concrete should not pursue a single optimum in workability or strength alone. Instead, coordinated performance among FA, BFS, MK, and DE is required to obtain superior overall applicability.

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