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Properties and applications of ultra-fine composite mineral admixtures prepared by fly ash

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Abstract. In recent years, with the rapid development of China's infrastructure and green high-performance concrete, as well as to achieve carbon peaking and carbon neutrality goals, the demand for green high-performance mineral admixtures is increasing. Ultra-fine composite mineral admixtures were meticulously crafted through the synergistic ultra-fine grinding of secondary fly ash and S95 mineral powder, incorporating varying ratios and a strategic quantity of grinding activator. This study delved into the fineness, specific surface area, fluidity ratio, setting time, activity index of these admixtures, the comparison with the main commercially available ultrafine powder, along with their application potential in cement and concrete. The findings underscore the remarkable performance of the admixtures, with a specific surface area reaching 780 m^2/kg, an activity index soaring to 118%, and a fluidity ratio exceeding 112%, all exceeding the technical benchmarks set for S95 and even approaching S105 mineral powder standards. When 20% of P·O42.5 cement was substituted with the ultra-fine composite mineral admixtures, the resulting composite cement exhibited a marginal extension in setting time, a marked enhancement in mortar fluidity, and a substantial boost in compressive strength at both 3 and 28 days. Furthermore, the admixtures demonstrated exceptional versatility in concrete applications, with a maximum addition of 170 kg/m^3, constituting 45% of the total binder content. Notably, upon replacing an equivalent amount of S95 mineral powder and reducing cement dosage by 50-140 kg/m^3, the workability of the concrete was significantly improved, accompanied by an increase in compressive strength at 3, 7, and 28 days. Given their exceptional economic performance and multifaceted benefits, the ultra-fine composite mineral admixtures hold immense potential for widespread adoption and promotion in the construction industry.

Keywords: activity index; compressive strength; fly ash; mineral admixtures; ultra-fine grinding

1. Introduction

In recent years, the scale of China 's highway, railway and other projects and civil commercial concrete has been expanding, as well as the carbon peaking and carbon neutrality goals, the demand for green high-performance mineral admixtures is increasing. In the process of cement production, there are some challenges to achieve the ideal particle size distribution to improve the performance and strength of cement (China Building Materials Federation 2022). Especially when the clinker particle size is too fine, the water demand of cement will increase significantly, which may lead to dry shrinkage of cement mortar and cracking of concrete. Therefore, it is necessary to grind the clinker to an appropriate fineness to make the cement paste structure denser (Lyngdoh *et al*. 2022). In the context of advancing sustainable development and circular economy, Fly Ash, a primary solid waste generated from industrial activities such as coal-fired power plants, has emerged as a focal point of shared interest among scientific researchers and industrial practitioners for its high-value and large-scale utilization. Recent years have witnessed a growing trend of technological innovations coupled with increasingly stringent environmental policies, which have facilitated the comprehensive utilization of Fly Ash. This not only alleviates environmental burdens but also promotes the effective transformation and value-added utilization of resources, thereby offering a vital pathway towards green economy and low-carbon development. It is evident that fly ash can be utilized as a cement mixture to replace clay in raw materials, and as an admixture in commercial concrete (Li *et al*. 2021). The use of fly ash in cement and concrete is common.

Wang *et al*. (2022) explores the impacts of numerous unconventional fly ashes-reclaimed, beneficiated off-spec, and marginal fly ashes on early and later-age properties of cementitious paste were assessed. Wi *et al*. (2024) explores the potential utilization of the fly ash produced from co-burning municipal solid waste (MSW) and natural gas in cement-based materials. Al-Shmaisani *et al*. (2022) research the variety of these blended fly ashes were examined and compared to a traditional siliceous fly ash. Akmalaiuly *et al*. (2023) show that a higher amount of untreated fly ash significantly prolongs the cement hydration process, decreases hydration temperature, deteriorates the structure and decreases compressive strength. Sun *et al*. (2021)

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indicate that compressive strength increases linearly with the increase of fly ash fineness.

Increasing its content in cement and concrete by enhancing its application performance has always been a focal point of research. Ultra-fine grinding is a crucial method for realizing the utilization of fly ash with superior quality, efficiency, and added value. Li *et al.* (2022) show that the cement fly-ash paste presented a reduction of water requirement and an elongation of setting time with the increased content of fly ash. Eker *et al.* (2023) determine the effect of fly ash added to concrete with high calcium content (C class) and different fineness on durability properties such as the alkali-silica reaction (ASR). Wang *et al.* (2024) indicated that under standard curing conditions, the mechanical properties of geopolymer pastes increased with the increase of NaOH solution concentration in alkaline activators. Sanker *et al.* (2020) presents the persuade of Fine Grinded Fly Ash (FGFA) and Silica Fume (SF) as a modified pozzolanic replacement to the binder. Krishnaraj and Ravichandrn (2020) investigations show the ultra-fine fly ash masonry block shows higher compressive strength, higher resistance to shear, higher bonding between two bricks compare to conventional masonry blocks.

Studies have shown that ultrafine mineral admixtures have three major effects: morphological effect, micro-aggregate effect and activation effect (Boopathi and Sharmila Devi 2019), which can improve the performance of cement and concrete, and the improvement effect of composite mineral admixtures is better than that of single admixtures (Sharma *et al.* 2022, Mucsi *et al.* 2016, Chen *et al.* 2021, Amin *et al.* 2020). At the same time, it can also reduce the production cost of cement and concrete. Therefore, Ultra-fine composite mineral admixture as a high functional cement and concrete admixture has a better application prospect (Tangadagi *et al.* 2021, Sun *et al.* 2021, Ajith *et al.* 2021). Most commercially available ultrafine powder cannot be applied to concrete in large quantities, the cost couldn't be reduced significantly. The preparation of ultrafine composite mineral admixtures with fly ash not only realizes the utilization of high quality, high effect and high amount of fly ash, but also replaces slag powder to alleviate the shortage of slag resources, and reduces the amount of cement and cement clinker, so as to achieves the purpose of reducing carbon and achieving green sustainable development (Zhuge *et al.* 2024). Agrawal and Savoika (2021) indicate that the use of FA binary combinations improves the workability but mechanical and durability properties are compromised. Ahmad *et al.* (2024) investigate the feasibility of partially replacing SF with two other pozzolanic waste materials, fly ash (FA) and natural pozzolan (NP), for UHPC production. Ganesan *et al.* (2023) investigate achieved a high-strength concrete by using 40% industrial waste, i.e., coal bottom ash, as a partial replacement of fine aggregates in combination with the 15% Alccofine inclusion as a partial replacement of cement. About 58% improvement in compressive strength was recorded for 40% coal bottom ash and 15% Alccofine mix.

The ultra-fine composite mineral admixtures were prepared by ultra-fine grinding means using different proportions of fly ash and mineral powder, along with the addition of certain grinding activator. The main physical and chemical indexes of the admixtures were tested. Experimental results indicate that the ultra-fine composite mineral admixture meets the technical requirements of S95 and even S105. It has been successfully applied in the production of composite cement and concrete, which enhances the performance and significantly lowers the cost. Based on the performance, application and economic benefits of ultrafine composite mineral admixtures, this study comprehensively discusses the performance changes of ultrafine composite mineral admixtures in partially replacing clinker in the cement industry, which can be used as a reference for the cement production industry. This work is helpful for the utilization of solid industrial waste and helps to achieve the goal of reducing carbon emission, reducing production cost and increasing the efficiency in the cement production industry.

2. Experiment

2.1 Experiment materials

Fly ash (F): grade 2, from a power plant located in Chiping County, Shandong province; Mineral powder (K): S95, from a steel plant in Dezhou City, Shandong Province; Activator: Self-made grinding activator; Standard sand: ISO standard, by Xiamen Aisiou Standard Sand Co., Ltd; Reference cement (SPC): Qufu Zhonglian Cement Co., Ltd, a subsidiary of China United Cement Group Co., Ltd; P·O42.5 cement (OPC): Jinan Shanshui Cement Co., Ltd; Ultrafine powder sample 1 (UF-S1): Shandong Dezhou Building Materials Co., Ltd.; Ultrafine powder sample 2 (UF-S2): Hebei Shijiazhuang Research Institute Co., Ltd.; Aggregate: Coarse aggregate is grade 2 gravel with a maximum particle size of 31.5 mm, while fine aggregate is machine-made sand with a fineness modulus of 3.2; Water reducing agent: Xika agent produced by a commercial mixing plant.

The main chemical composition and physical indexes of P·O42.5 cement, fly ash and mineral powder are presented in Tables 1-2.

Table 1 The main chemical compositions of raw materials (wt%)

Raw materials	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Cl^-	Loss on ignition
OPC	63.54	4.62	19.71	2.85	1.26	2.28	0.13	0.54	0.02	2.5
F	14.22	17.50	51.66	3.59	1.48	1.0	1.20	1.58	0	4.57
K	42.66	9.80	39.12	1.57	2.49	1.56	0.98	2.52	0.02	0.64

Table 2 The main physical indexes of raw materials

Raw materials	Fineness (45 μm square hole sieve sieve residue/%)	Specific surface area / (m²/kg)	Water demand ratio/%	Fluidity ratio /%	Strength activity/%	
					7 d	28 d
OPC	4.54 (80 μm sieve residue)	376	/	/	/	/
F	5.88	345	102	/	60	74
K	2.72	410	/	97	78	99

Table 3 The experiment scheme for preparation of composite mineral admixtures (wt%)

Serial number	F	K	Grinding activator	Ultra-fine grinding time/min
UF-1	60	40	0.05	0
UF-2	50	50	0.05	0
UF-3	40	60	0.05	0
UF-4	60	40	0.05	60
UF-5	50	50	0.05	60
UF-6	40	60	0.05	60

2.2 Experiment scheme

Scheme 1: Fly ash and mineral powder were mixed in varying proportions with a specific amount of grinding activator added. The fineness, specific surface area, fluidity ratio, setting time, and activity index were analyzed. The fly ash content was ranged from 60%, 50%, to 40%, the grinding activator content remained at 0.05%.

Scheme 2: The samples from Scheme 1 underwent ultra-fine grinding for 60 min to create ultra-fine composite mineral admixtures. Fineness, specific surface area, fluidity ratio, setting time, and activity index were measured. Table 3 outlined the experimental parameters.

2.3 Experiment method

The fineness, specific surface area, setting time, mortar fluidity and mortar strength of each cementitious material were tested. The tests were carried out according to the current national standard GB/T 1345-2005 'Cement fineness test method sieve analysis method', GB/T 8074-2008 'Cement specific surface area determination method (Brinell method)', GB/T 1346-2017 "Test methods for water requirement of normal consistency, setting time and soundness of the cements", GB/T 2419-2005 "Test method for fluidity of cement mortar" and GB/T 17671-2017 "Method of testing cements--Determination of strength (ISO method)". The mortar test blocks were cured for 3 d, 7 d, and 28 d before testing their flexural and compressive strength using the TYE-300E integrated testing machine.

Table 4 The main chemical components of the samples prepared by different schemes (wt%)

Raw materials	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Cl^-	Loss on ignition
UF-1	25.64	15.21	47.34	2.58	1.75	1.19	1.07	1.88	0	3.29
UF-2	28.87	13.92	45.59	2.35	1.98	1.27	0.99	1.95	0	2.75
UF-3	31.35	12.77	44.11	2.31	2.13	1.30	0.96	2.12	0.01	2.02
UF-4	26.46	15.89	48.15	2.34	1.72	1.05	0.97	1.76	0	0.99
UF-5	29.09	14.65	46.38	2.11	1.91	1.13	0.92	1.83	0	0.85
UF-6	32.28	13.57	45.14	1.96	2.02	1.21	0.89	1.98	0.01	0.72
UF-S1	23.79	15.06	48.25	2.83	1.84	1.20	1.17	2.09	0.01	3.76
UF-S2	26.35	14.92	46.91	2.55	2.10	1.32	1.05	2.02	0.01	2.77

Table 5 The main physical indexes of samples prepared by different schemes

Raw materials	Fineness (the sieve residue through 45 μm square hole sieve /%	Specific surface area/ (m²/kg)	Water demand ratio/%	Fluidity ratio /%	Strength activity/%	
					7 d	28 d
UF-1	8.2	375	95	147	65	82
UF-2	7.9	383	94	145	67	87
UF-3	7.8	390	95	140	71	90
UF-4	0.9	780	112	134	88	106
UF-5	1.0	755	110	125	91	110
UF-6	1.2	742	108	124	95	118
UF-S1	3.1	638	99	140	77	98
UF-S2	2.5	685	102	138	82	101

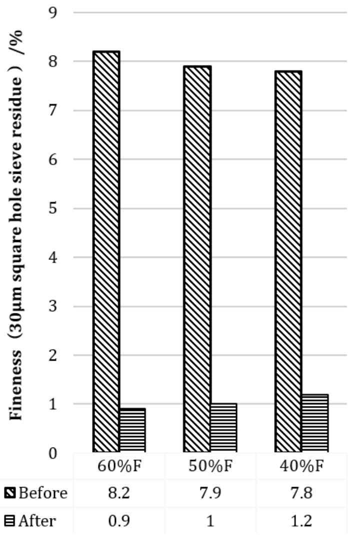

Fig. 1 The fineness before and after ultra-fine grinding for 60 min

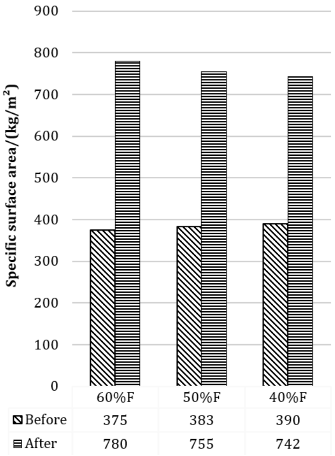

Fig. 2 Specific surface area before and after ultra-fine grinding for 60 min

3. Results and discussion

3.1 Experiment results

After ultra-fine grinding for 60 min, the results of different test schemes are shown in Tables 4-5.

3.2 The effect of ultra-fine grinding on fineness and specific surface area of composite mineral admixture

Figs. 1-2 illustrate the changes in fineness and specific surface area of composite mineral admixtures with different fly ash contents before and after 60 min of ultra-fine grinding. The results indicate a significant increasing in both fineness and specific surface area for the grinding process. For the composite mineral admixture containing 60% fly ash, the sieve residue through the 30μm square hole sieve decreased from 8.2% to only 0.9% after grinding. The specific surface area increased to 780 m^2/kg after grinding, 108% higher than the pre-grinding value.

This is due to the special design and transformation of the ball mill and the grinding body. After the three-stage grinding of the ball mill, the gradation of the grinding body is more reasonable, and the high-performance grinding activator was added. The ultra-fine grinding time is prolonged, the grinding is more sufficient, and the fine powder is not easy to agglomerate, which greatly improves the fineness and specific surface area of the mineral admixture.

3.3 The effect of ultra-fine grinding on fluidity ratio and initial setting time ratio of the composite mineral admixtures

Figs. 3-4 illustrate the fluidity and initial setting time ratio of the composite mineral admixtures with varying fly ash contents before and after 60 min of ultra-fine grinding, respectively. In Fig. 3, the fluidity ratios of the admixtures with 60%, 50%, and 40% fly ash content are 112%, 110%, and 108% after the grinding, respectively. They are 18%, 17%, and 14% higher than those of before the grinding, surpassing the fluidity ratio GB standard not less than 95%. The enhancement in fluidity can be ascribed to the ball-

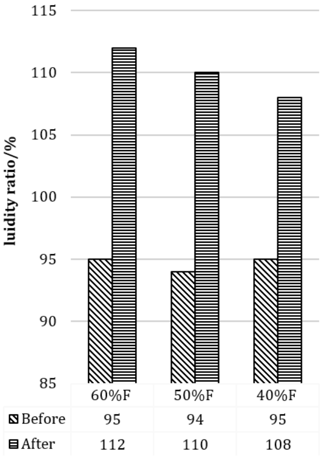

Fig. 3 The fluidity ratio before and after ultrafine grinding for 60 min

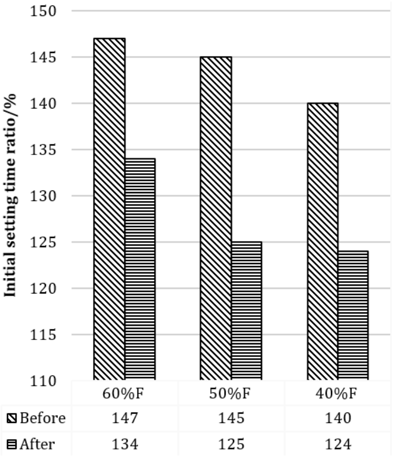

Fig. 4 Ratio of initial setting time before and after ultra-fine grinding for 60 min

bearing effect exhibited by ultra-fine grinding particles. On one hand, these particles effectively fill the interstitial spaces between the cement paste and flocculated structures, thereby mitigating the internal resistance encountered by the slurry during flow. Consequently, this leads to a notable improvement in fluidity (Libre *et al*. 2010). On the other hand, after the ultra-fine particles are filled in the structural voids of the cement paste, the structure is more dense, so that part of the water originally filled in the voids overflows, the free water in the slurry increases, and the fluidity increases (Ting *et al*. 2019).

In Fig. 4, the initial setting time ratio of composite mineral admixture decreases to varying degrees after 60 min of ultra-fine grinding. This reduction is a result of the significantly improved specific surface area of the composite mineral admixture and enhanced hydration contact area, leading to accelerated hydration and advancement of the initial setting time post-grinding at the same dosage.

3.4 The effect of ultra-fine grinding on the activity index of the composite mineral admixtures

Fig. 5 shows the 7 d and 28 d activity index of the composite mineral admixtures with different fly ash content before and after the ultra-fine grinding for 60 min.

It can be seen from Fig. 3 that the activity index is greatly improved after ultra-fine milling. For the admixture with 60% fly ash, the 7 d and 28 d activity indexs are 88% and 106% respectively, which are 35% and 29% higher than that before ultra-fine grinding and meets the technical requirement of S95 mineral powder in GB/T 18046. For the admixture with 40% fly ash. The 7 d and 28 d activity indexs are 96% and 118%; which are 35% and 31% higher than that before ultra-fine grinding and meet the technical requirements of S105 mineral powder in GB/T 18046, and the 28 d activity index is much higher than the GB standard requirement's 105%. It is mainly the combination result of the two following factors (Wu *et al*. 2021):

(1) Activity effect: The data in Table 4 show that after the ultra-fine grinding of the composite mineral admixtures, SiO_2, Al_2O_3 and other oxides' contents increased. This is because under the continuous mechanical force, the particles become finer, the surface activation energy is reduced, and more active oxides such as SiO_2 and Al_2O_3 are dissolved out of the surface under this mechanical action, and react with the calcium hydroxide originated by the cement hydration to generate more calcium silicaluminate gel, which plays an activity effect and increases the activity index.

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4. The application of the ultra-fine composite mineral admixtures in the cement and concrete

Based on the experimental data and the economy in practical application, UF-4 was selected for the cement and concrete application test. The ultra-fine composite mineral admixture was prepared by 60 min of ultra-fine grinding using 60% fly ash, 40% mineral powder, and 0.05% grinding aid activator. The activity indexes for 7 d and 28 d were 88% and 106%, meeting the technical requirements of S95 mineral powder.

The performance indexes of UF-4, UF-S1 and UF-S2 are compared as follows : Table 6, and the same test scheme is used to prepare composite cement and concrete.

4.1 The application of the ultra-fine composite mineral admixture in the preparation of composite cement

The composite cements PC-1, PC-2, PC-3 and PC-4 were created by substituting 20% of P·O42.5 cement with

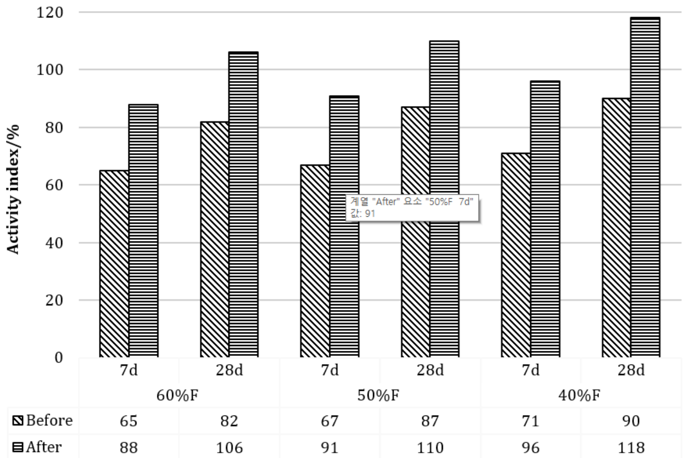

Fig. 5 Activity index before and after ultra-fine grinding for 60 min

Table 6 Physical performance indexes of UF-4, UF-S1 and UF-S2

Serial number	Fineness (30 μm square hole sieve residue)/%	Specific surface area /(m^2/kg)	Fluidity ratio/%	Initial setting time ratio/%	Activity index/%	
UF-4	0.9	780	112	134	88	106
UF-S1	3.1	638	99	140	77	98
UF-S2	2.5	685	102	138	82	101

Table 7 The detailed scheme for preparing composite cement (wt%)

Serial number	P·O42.5	UF-4	K	Preparation
Blank sample	100	/	/	P·O42.5 finished product
PC-1	80	20	/	P. O42.5 mixed with UF-4 15 min
PC-2	80	/	20	P. O42.5 mixed with UF-S1 15 min
PC-3	80	20	/	P. O42.5 mixed with UF-S2 15 min
PC-4	80	/	20	P. O42.5 mixed with K 15 min

Table 8 The test results of different cement samples

Serial number	Fluidity mortar/mm	Setting time/h: min		Compressive strength/MPa	
		Initial setting	Final setting	3 d	28 d
Blank sample	150	2:05	3:40	28.3	49.8
PC-1	165	2:20	4:00	30.7	54.4
PC-2	150	2:55	4:37	26.8	50.7
PC-3	153	2:52	4:28	27.2	51.5
PC-4	147	2:30	4:25	29.0	51.6

UF-4, UF-S1, UF-S2 ultra-fine admixture and mineral powder, respectively. The performance indicators were then compared to that of the control sample of P·O42.5 cement. The specific methodology and test outcomes can be found in Tables 7-8.

It can be seen from the data in Table 8 that the fluidity of the composite cement PC-1 prepared by the ultrafine composite mineral admixture UF-4 instead of 20% of the finished product P·O42.5 was significantly improved compared with the blank sample, and the increase was 110 %. And it is obviously better than the composite cement PC-2, PC-3 and PC-4 prepared by the other two samples UF-S1, UF-S2 and mineral powder. It is consistent with the fluidity ratio data in Table 6, which is mainly due to the 'ball' effect of ultrafine particles. The setting time was slightly longer than that of the blank sample, which was between the blank sample and PC-4. From the compressive strength data, the strength of PC-1, PC-2 and PC-3 mixed with ultrafine composite mineral admixtures is higher than that of blank samples. Among them, the compressive strength of PC-1 composite cement at 3 d and 28 d was 30.7 MPa and 51.5 MPa, respectively, which was 2.4 MPa and 4.5 MPa higher than that of blank sample at 3 d and 28 d, with an increase of 8.5% and 9.2%, respectively, and the strength was also significantly better than that of PC-2, PC-3 and PC-4. The data in the table show that the composite cement prepared by UF-4 ultrafine composite mineral admixture has excellent performance, exceeding the strength requirements of P·O42.5 cement, and the performance is better than that of the composite cement prepared by mineral powder, which can reduce the amount of clinker in the cement and save the cost. According to the market situation, the price of ultrafine mineral composite admixture is 80~100 yuan/ton lower than the price of finished P·O42.5 cement. With the output of 1 million tons/year, a cement plant can reduce the cost by about 16~20 million yuan per year by replacing 20% P·O42.5 with ultrafine mineral composite admixture.

4.2 The application of the ultra-fine composite mineral admixture in concrete production

4.2.1 UF-4 superfine composite mineral admixture used in the production of C30 and C50 concrete

The UF-4 ultra-fine composite mineral admixtures were applied to concrete making. The low grade C30 and high grade C50 concrete from a commercial concrete mixing plant were used in the experiment. Adjustments were made to the benchmark concrete mix ratios. The work-ability of the concrete was tested, compressive strength was measured at 3 d, 7 d, and 28 d. Tables 9-10 are the specific methodology and results.

The results from Tables 9-10 show that as the amount of UF-4 ultra-fine composite mineral admixtures usage increases, the slump and the expansion of the concrete increase correspondingly, along with the fluidity. It suggests that the ultra-fine particles have a 'ball' effect on the

Table 9 The experiment scheme of different mix ratio of UF-4 applied to concrete

Serial number	Concrete strength grade	Concrete mix ratio/(kg/m^3)	UF-4 dosage /(kg/m^3)
F0	C30	Cement : Fly ash : Mineral powder : Gravel : Machine-made sand : Water reducing agent : Water = 250 : 65 : 80 : 890 : 925 : 10 : 180	0
F1		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 250 : 65 : 80 : 890 : 925 : 10 : 180	80
F2		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 214 : 60 : 110 : 916 : 915 : 9.5 : 175	110
F3		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 180 : 60 : 130 : 925 : 924 : 9.2 : 172	130
F4		Cement : Fly ash : UF-4 : Gravel : Machine-made and : Water reducing agent : Water = 170 : 60 : 150 : 919 : 919 : 9 : 173	150
F5		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 150 : 60 : 170 : 919 : 919 : 9 : 173	170
F6	C50	Cement : Fly ash : Mineral powder : Gravel : Machine-made sand : Water reducing agent : Water = 420 : 50 : 50 : 1000 : 752 : 12 : 166	0
F7		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 420 : 50 : 50 : 1000 : 752 : 12 : 166	50
F8		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 360 : 50 : 110 : 1000 : 752 : 12 : 166	110
F9		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 330 : 50 : 130 : 1008 : 758 : 11.5 : 163	130
F10		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 300 : 50 : 150 : 1027 : 772 : 11 : 160	150
F11		Cement : Fly ash : UF-4 : Gravel : Machine-made sand : Water reducing agent : Water = 280 : 50 : 170 : 1050 : 730 : 10.5 : 160	170

*Note: F0~F5 for C30 concrete mixture ratio, F6~F11 for C50 concrete mix proportion; The principle for the mix ratio adjustments not changing the bulk density of the concrete and the water-binder ratio

Table 10 The experiment results of different mixtures of UF-4 applied to concrete

Serial number	Initial slum /mm	Initial expansion /mm	Initial work-ability	60 min slum /mm	60 min expansion /mm	Compressive strength/MPa		
						3 d	7 d	28 d
F0	200	500	Good	190	460	23.8	33.8	44.7
F1	205	510	Good	200	480	24.6	34.3	44.8
F2	210	540	Good	200	510	25.1	36.9	46.2
F3	220	570	Good	210	530	25.7	38.5	47.0
F4	220	570	Good	215	540	25.4	39.0	47.3
F5	225	570	Good	215	530	26.3	40.3	47.9
F6	220	550	Good	200	460	46.1	55.2	60.8
F7	220	560	Good	210	500	45.9	55.7	61.1
F8	225	570	Good	220	560	46.7	56.3	62.5
F9	230	580	Good	220	570	47.5	56.6	63.2
F10	240	600	Good	235	580	48.0	57.5	65.3
F11	240	595	Good	230	580	48.1	57.0	65.9

concrete, consistent with the observation of the enhanced mobility for previous samples (refer to Figs. 6-7). Additionally, testing revealed that C30 concrete with UF-4 added exhibited better encapsulation and cohesiveness compared to those of the base concrete, and the slump loss was relatively smaller. The new C50 concrete was lighter and less sticky, making it more suitable for construction purposes.

Figs. 8-9 illustrate the compressive strength of C30 and C50 concrete at various ages. The addition of UF-4 ultra-fine composite mineral admixture enhances the compressive strength of concrete at 3 d, 7 d, and 28 d ages within

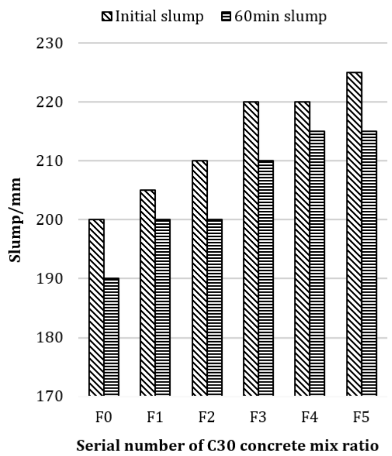

Fig. 6 Initial and 60 min slump of C30 concrete with different mix proportions

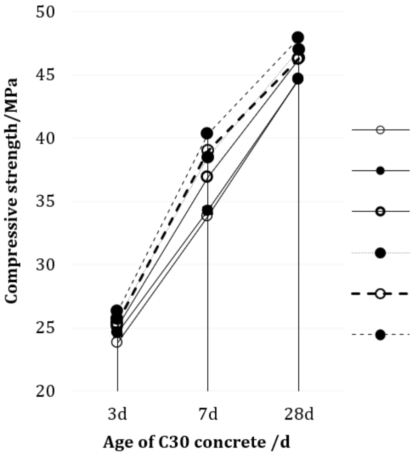

Fig. 8 Compressive strength of C30 concrete with different mix proportions and different ages

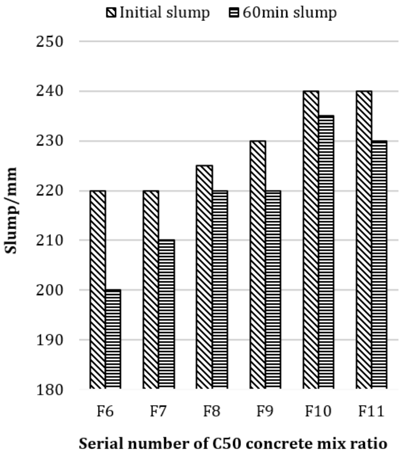

Fig. 7 Initial and 60 min slump of C50 concrete with different mix proportions

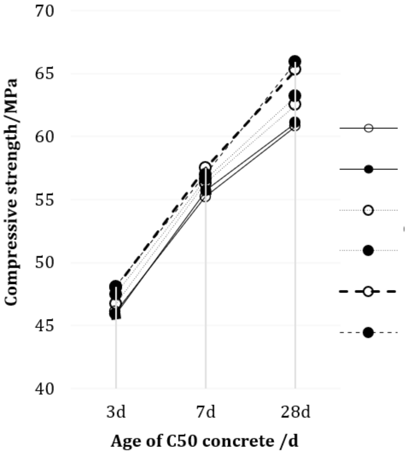

Fig. 9 Compressive strength of C50 concrete with different mix proportions and different ages

a reasonable mixed amount. The strength of concrete increases notably with higher UF-4 proportion. For instance, the 28 d compressive strength of C30 concrete with 80 kg/m^3 UF-4 is 44.8 MPa, almost the same as that of the benchmark concrete with mineral powder at. However, adding 110 kg/m^3, 130 kg/m^3, 150 kg/m^3, and 170 kg/m^3 UF-4, substituting mineral powder along with reducing cement uasge by 36 kg/m^3 to 100 kg/m^3, results in 28 d compressive strengths of 46.2 MPa, 47.0 MPa, 47.73 MPa, and 47.9 MPa respectively.

4.2.2 Performance comparison of UF-4, UF-S1 and UF-S2 used in the production of C30 and C50 concrete

The C30 concrete mix ratio F5 and C50 concrete mix ratio F11 were selected for the test. The admixtures were UF-4 and UF-S1, UF-S2, respectively, and compared with the C30 and C50 reference concrete mixed with mineral powder K. The performance comparison is as followings : Table 11.

From the data in Table 11, it can be seen that for C30 concrete, in the case of a relatively large water-binder ratio, after adding ultra-fine composite mineral admixtures UF-4, UF-S1, UF-S2, the initial workability of concrete is obviously better than that of the reference concrete with mineral powder K. This is due to the very fine particles of ultra-fine powder, large specific surface area, uniform coating of concrete aggregate, richer slurry, and better workability. After 60 min, the slump loss of concrete mixed with UF-4 is small, and the workability is still good, while the concrete mixed with UF-S1 and UF-S2 is the same as the reference concrete, the slump loss is large and the workability is poor. According to the strength data of C30 concrete at different ages, after adding 170 kg/m^3 UF-4, the mineral powder is completely replaced and the amount of cement is reduced by 100 kg/m^3, and the total amount of glue is also reduced by 10 kg/m^3. The strength of each age is significantly higher than that of the reference concrete. With the same mix proportion, after adding UF-S1 and UF-S2, the strength of each age is significantly lower than that of the reference concrete.

For C50 concrete, when the water-binder ratio is relatively small, the initial workability of concrete mixed with UF-4 is obviously better than that of the reference concrete mixed with mineral powder K. The slurry is soft, not as sticky and heavy as the reference concrete, and more

Table 11 Performance data of C30 and C50 concrete prepared by UF-4, UF-S1 and UF-S2

Serial number	Admixture	Initial slump /mm	Initial expansion /mm	Initial workability	60 min slump /mm	60 min expansion /mm	Compressive strength /MPa		
							3 d	7 d	28 d
F0	K	200	500	Good	190	460	23.8	33.8	44.7
C301	UF-4	225	570	Good	215	530	26.3	40.3	47.9
C302	UF-S1	210	530	Good	190	460	17.5	25.2	32.1
C303	UF-S2	215	540	Good	200	480	18.0	27.6	34.3
F6	K	220	550	Good	200	460	46.1	55.2	60.8
C501	UF-4	240	595	Good	230	580	48.1	57.0	65.9
C502	UF-S1	225	550	General	200	480	26.7	40.5	51.8
C503	UF-S2	225	560	Better	210	480	28.0	42.4	53.0

conducive to construction. After adding UF-S1 and UF-S2, the C50 concrete slurry is more viscous, the flow is slower, similar to the reference concrete, and it is more difficult to construct. According to the strength data of different ages, after adding 170 kg/m^3 UF-4, the mineral powder is completely replaced and the amount of cement is reduced by 140 kg/m^3, and the total amount of rubber is reduced by 20 kg/m^3. The strength of each age is significantly higher than that of the reference concrete. After adding UF-S1 and UF-S2, the strength at each age is lower than that of the reference concrete, and even lower than the standard design strength requirements of C50 concrete.

From the application of C30 and C50 concrete, it shows that the two commercially available samples cannot be applied to concrete in large quantities, nor can they greatly reduce the amount of cement, and the cost savings are limited. Their quality performance is much lower than that of the ultrafine composite mineral admixture in this study, which may be related to the raw material quality, formula, particle gradation and other factors of the ultrafine composite mineral admixture.

4.2.3 Economic analysis of ultra-fine composite mineral admixture used in concrete

Economically, the market price of the ultra-fine composite mineral admixture is significantly lower, the price is 80~100 yuan/ton lower than that of cement. The annual production of C30 concrete in commercial mixing station is 300,000 m^3. Adding 170 kg/m^3 ultrafine composite mineral admixture can reduce 100 kg/m^3 cement. The cost of concrete can be saved by 8~10 yuan per square meter, and the cost can be saved by 2.4~3 million per year. The concrete using the new ultra-fine admixture not only enhances its work-ability and compressive strength but also reduces the cement usage, making it cost-effective and more conducive to construction.

5. Conclusions

To further lower carbon emission by increasing the replacement amount of cement or the amount usage in concrete and to improve the properties of the commercially available ultrafine powder, the composites were prepared using different proportions of fly ash and mineral powder, along with a certain grinding activator. Their fineness, specific surface area, setting time, mortar fluidity and mortar strength were tested following the procedures outlined previously, and the economic benefits were analyzed. The main conclusions obtained are as follows:

- Fly ash and mineral powder are combined in different ratios and subjected to the ultra-fine grinding to produce an ultra-fine composite mineral admixture. This process significantly enhances the fineness, the specific surface area, the fluidity ratio, and the activity index, the admixture meets the criteria for S95 mineral powder and even reaches to S105 levels, and the performance is significantly better than the commercially available ultrafine powder UF-S1 and UF-S2.
- When this ultra-fine composite mineral admixture replaces 20% of P·O42.5 cement, the setting time of the composite cement is slightly prolonged and the fluidity of the colloidal sand substantially increases 110%. The compressive strength at 3 d and 28 d increases 8.5% and 9.2%, respectively. However, commercially available UF-S1 and UF-S2 cannot be applied to concrete in large quantities, nor can they significantly reduce the amount of cement.
- This ultra-fine admixture can be used in concrete in a substantial amount, up to 170 kg/m^3, representing 45% of the total adhesive material used. By replacing an equivalent amount of S95 mineral powder, cement consumption can be reduced by 50-140 kg/m^3, the work-ability and the compressive strength at 3 d, 7 d, and 28 d are enhanced. It indicates that the use of the ultra-fine composite mineral admixture in concrete is beneficial for construction, offering both improved performance and cost-effectiveness.
- The performance of the ultrafine composite minerals prepared by this research is generally better than that of the main commercially available ultrafine powder UF-S1 and UF-S2. In the application of preparing composite cement and concrete, it can save clinker, replace mineral powder, reduce the amount of cement, greatly save costs, alleviate the shortage of

slag resources, reduce carbon emissions, and achieve green and sustainable development. It is worth promoting.

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