

Original Paper

Research on the Reasonable Range of Stone Chip Fineness Modulus and Factors Affecting Concrete Technical Properties

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Abstract

This study investigates the effect of the stone chip fineness modulus on concrete workability, mechanical properties, and durability to establish an acceptable fineness modulus range. In the fineness modulus range (2.1–3.3), the concrete slump tends to increase and then decrease as the fineness modulus of the stone chips increases, reaching its maximum value at 3.2. Higher fineness modulus increase concrete mix's segregation and water secretion. The mechanical strength tends to first increase and then stabilize, becoming almost unaffected when the fineness modulus exceeds 2.6. The penetration depth, mass loss rate, and compressive strength loss rate are found to increase, indicating that as the fineness modulus increases, concrete durability worsens. Therefore, the recommended range for the stone chip fineness modulus is 2.6–3.2 for preparing stone chip concrete.

Keywords

Stone chip concrete, gradation, fineness modulus, construction workability, mechanical performance, durability

1. Introduction

Except for sand-free concrete, sand is an important component of concrete, accounting for 30%–40% of its total mass. Natural and artificial sands are frequently used in building (Aboagye et al., 2025). Natural river sand has long been regularly mined in a disorderly and illegal manner, and the mining cost is extremely low, resulting in a severe supply shortage and continuous price increase in recent years (Dudka et al., 1997; Da et al., 2022; Troisi et al., 2016). Considering the advancement in engineering construction, artificial sand will become the primary development path for construction sand. Artificial sand includes stone chips, mechanism sand, and industrial solid waste sand making. Stone chips refer to the underscreen

part of aggregate with a 2.36 or 4.75 mm sieve, whereas mechanism sand refers to rock particles with a particle size of less than 4.75 mm after mechanical crushing (Hashim et al., 2011). Stone chips and mechanism sand are produced using different methods, which have some drawbacks such as poor grading, needle-like granular particles, and high powder content. These factors are thought to prevent these materials from being used as fine aggregate in concrete, converting them into industrial waste, which deviates from the development direction of the sand and gravel industry (Shen et al., 2022; Zhu et al., 2023). However, many researchers have questioned this viewpoint. To maximize the use of stone chips in the construction of concrete projects, several researchers have undertaken considerable research on stone chips and stone chip concrete. A representative engineering case is the Dalian Bay undersea immersed tube tunnel in China, where manufactured sand high-performance concrete was adopted and its strength and durability were systematically evaluated and verified through laboratory tests and field application (Ruan et al., 2024). In addition, the specifications of different countries specify different upper limits for the fines (stone powder) content permitted in manufactured sand (Aboagye et al., 2025). Because of these investigations, the application of stone chips in concrete engineering is now feasible. Li et al. investigated the effect of stone powders with different parent rock lithologies on the properties of cementitious materials and reported that limestone and tuff powders shortened the setting time, that an appropriate stone powder content reduced drying shrinkage, and that increasing the fineness of the powder decreased the proportion of harmful pores (Li et al., 2021). Shen et al. developed a cleaner production process for high-quality manufactured sand combined with the ecological utilization of recycled stone powder and reported that digital regulation of the stone powder content improved the workability and compressive strength of manufactured sand concrete by average values of 16.19% and 7.1%, respectively (Shen et al., 2022). Zheng et al. studied the effect of fines content on the durability of high-strength manufactured sand concrete and showed that when the fines content was below 15%, the resistance to chloride ion and sulfate penetration was effectively improved, and the carbonation depth reached its minimum at a fines content of 10% (Zheng et al., 2023). Qian et al. investigated the shrinkage and durability of concrete prepared with waste rock manufactured sand and found that the early-age shrinkage was 8.5%–32.4% higher than that of river sand concrete, whereas the long-term shrinkage after 3 d of curing was 4.3%–13.9% lower (Qian et al., 2026). Nikzad et al. examined the effect of sand fineness modulus on the properties of self-compacting concrete and lightweight self-compacting concrete and found that increasing the fineness modulus from 2.3 to 3.1 improved the fluidity and passing ability and increased the compressive strength by approximately 20%, while reducing the segregation resistance (Nikzad et al., 2024). Wang et al. investigated the early-age hydration, mechanical property development, and microstructure evolution of manufactured sand concrete containing granite stone powder and found that macropores larger than 1000 nm had the greatest influence on strength and that the roughness of the interfacial transition zone increased with the stone powder content (Wang et al., 2023). Shang et al. used solid waste from tunnel excavation to prepare manufactured sand with different lithologies and, combined with a pre-washing process, produced eco-friendly ultra-high-performance concrete; the pre-

washing process increased the fluidity by 16%–20%, and the mixture prepared with tuff manufactured sand achieved a 28d compressive strength exceeding 150MPa (Shang et al., 2004). Hor et al. prepared ultra-high-performance concrete in which manufactured sand replaced 70% of the quartz sand and reported an 8.8% increase in the 28d compressive strength, a cost reduction of 380 CNY/m³, and a CO₂ emission reduction of 14.2 kg/m³ (Hor et al., 2017).

The foregoing discussions reveal that many studies have explored stone chips and stone chip concrete, with the majority focusing on the direction of stone powder content. As the fineness modulus of stone chips has a significant impact on concrete technical properties, the existing technical standards are too broad for the grading range; although various stone chips can meet the technical standards for engineering sand, the technical properties vary greatly, resulting in different stone chip concrete with varying performances. Related studies have not systematically studied the performance of stone chip concrete and its technical properties. Therefore, this study explores the technical performance of stone chip concrete, investigates the influence of stone chip fineness modulus on the performance of concrete formulated by it, and proposes a reasonable range of stone chip fineness modulus to promote the standardization, scale, and high-quality application of stone chip in engineering construction, which can alleviate the problems of capital, schedule, and quality caused by the shortage of sand for engineering construction.

2. Materials

2.1 Raw Coating Materials

2.1.1 Cement

The test cements were Tongli P.O32.5, P.O42.5, and P.O52.5 cements, which were used to prepare C30, C40, and C50 concrete types, respectively. Their technical properties are shown in Table 1.

Table 1. Technical indicators of cement

Cement	Fineness (m ² /kg)	Setting time (min)		Bending strength (Mpa)		Compressive strength (Mpa)	
		Initial setting	Final setting	3d	28d	3d	28d
P.O32.5	350	217	254	5.1	7.7	28	36.8
P.O42.5	370	285	333	5.5	8.6	29.5	49.9
P.O52.5	380	190	241	6.0	10.1	32.4	54.5

2.1.2 Coarse Aggregate

The coarse aggregates of each grade for the test were limestone-crushed stones, and their technical properties are shown in Table 2.

Table 2. Technical Properties of Coarse Aggregate

Items	The following particle size (mm) coarse aggregate technical index measurement values	
	4.75–9.5	9.5–26.5
Apparent density (kg/m ³)	2721	2767
Mud content (%)	0.1	0.3
Needle flake content (%)	12.9	7.6
Ruggedness (%)		3.7
Crushing value (%)		18.5

2.1.3 Stone Chip

The stone chips used in the test were limestone chips, and their technical properties are shown in Table 3.

Table 3. Technical Properties of the Stone Chip

Items	Apparent density (kg/m ³)	Stone dust content (%)	Mud powder content (%)	Water absorption (%)	Crushing value (%)
Test value	2728	8.9	0.2	1.3	20.0

2.1.4 Admixture

The test admixtures were molasse water-reducing agents with a water reduction rate of 15% and polycarboxylic acid high-efficiency water-reducing agents with a water reduction rate of 38%. The former agent was used to prepare the C30 and C40 concrete required for the test, and the latter agent was used to prepare the C50 concrete required for the test.

2.2 Mixture Ratio

2.2.1 Cement Concrete

The ratio design of each strength grade of cement concrete is listed in Table 4. A design slump of 150 mm was selected.

Table 4. Cement Concrete Mix Ratio

Strength grade	Water-binder ratio	Sand ratio (%)	Amount of each material (kg/m ³)				
			Cement	Gravel	Stone chip	Water	Water Reducer
C30	0.50	37	360	1140	670	180	5
C40	0.48	37	375	1194	701	180	5
C50	0.36	36	469	1224	688	169	5

2.2.2 Coarse Aggregate

Table 5 lists the coarse aggregate gradation used in the test.

Table 5. Coarse Aggregate Grading

Gradation type	The following particle sizes (mm) coarse aggregate cumulative sieve residue (%)					
	26.5	19	16	9.5	4.75	2.36
Lower limit of specification grading	0	-	30	-	90	95
Test grading	0	7.8	30.2	83.9	98.9	99.7
Upper limit of specification grading	5	-	70	-	100	100

3. Tests Planning

3.1 Construction Workability Test

The construction workability test was conducted following the procedures for the slump test outlined in the “Standard for Test Method of Performance on Ordinary Fresh Concrete”. The test equipment is shown in Figure 1.



(a) HJS-60 type concrete double horizontal shaft mixer

(b) Standard slump cone bucket

Figure 1. Concrete Slump Test Apparatus

3.2 Mechanical Performance Test

The mechanical property tests included cube compressive strength (f_{cu}), axial compressive strength (f_{cp}), splitting tensile strength (f_{ts}), bending tensile strength (f_{ct}), and elastic modulus (E) tests, all of which were conducted with reference to the “Standard for Test Methods of Concrete Physical and Mechanical Properties”, and the test specimens were of standard size. The test apparatus used for the compressive strength test was the HYE-2000 pressure testing machine, the splitting tensile strength test apparatus was the WAW-1200B universal material testing machine, and the elastic modulus test apparatus was the YAW-2000M pressure testing machine (Figure 2).



(a) HYE-2000 pressure testing machine

(b) WAW-1200B universal material testing machine

(c) YAW-2000M pressure testing machine

Figure 2. Mechanical Properties Test Equipment

3.3 Durability Test

The durability performance test included the permeability resistance and freezing resistance tests of concrete, which were conducted with reference to the “Standard for Test Methods of Long-Term Performance and Durability of Ordinary Concrete”, and the test specimen size was the standard size. The apparatus used for the permeability test was the HS-40A concrete penetration apparatus (Figure 3). In the concrete permeability test, the standard concrete permeability specimens with different fineness modulus of stone chips prepared for an age of 28 d, with top and bottom diameters of 175 and 185 mm, respectively, and a height of 150 mm, were placed on the HS-40A concrete permeameter. After 24 h of constant pressure at 1.2 ± 0.05 MPa water pressure, the following procedures were taken: remove the specimen and place it on the press, fracture the section along the longitudinal section, trace the water infiltration trace line with a waterproof marker, measure the water infiltration height of 10 measurement points at equal intervals along the water infiltration trace line with a steel ruler, and take the average value as the specimen water infiltration height according to Eq. (1). The water infiltration height of a group of specimens is the average of 6 specimens. The water seepage height of a group of specimens is the average of 6 specimens calculated using Eq. (2).

$$\bar{h}_i = \frac{1}{10} \sum_{j=1}^{10} h_j \quad (1)$$

$$\bar{h} = \frac{1}{6} \sum_{i=1}^6 \bar{h}_i, \quad (2)$$

where h_j is the water seepage height at the “j” measurement point of the “i” specimen, $\bar{h}_i$ is the average seepage height of the “i” specimen, and $\bar{h}$ is the average seepage height of a group of 6 specimens.

In the freezing resistance test of concrete, when the mass loss rate of concrete specimens exceeds 5% or the compressive strength loss rate reaches 25%, the number of freeze-thaw cycles is the freezing

resistance grade of concrete. The mass loss rate of the concrete specimen and the cube compressive strength loss rate are calculated according to Eqs. (3) and (4), respectively.

$$\Delta M_n = \frac{m_0 - m_n}{m_0} \times 100\% \quad (3)$$

$$\Delta f_{cu}(n) = \frac{f_{cu0} - f_{cun}}{f_{cu0}} \times 100\%, \quad (4)$$

where ΔM_n is the mass loss rate of concrete specimens after “n” times freeze-thaw cycles, m_i is the quality of concrete specimens after “i” times freeze-thaw cycles, $\Delta f_{cu}(n)$ is the degradation coefficient of cubic compressive strength of concrete specimens after “n” times freeze-thaw cycles, f_{cui} is the cubic compressive strength of concrete after “i” times freeze-thaw cycles.



Figure 3. Concrete Penetrometer

3.4 Test Plan

Table 6 lists the sieving results of the stone chips for the test. According to the range of particle gradation of sand in Zone II of "Sand for Construction," six different gradation types of sand with fineness modulus ranging from 2.1 to 3.3 were used to prepare stone chip concrete with different fineness modulus to study their effects on the construction workability, mechanical properties, and durability performance of concrete (Table 7).

Table 6. Stone Chip Sieving Results

The following particle size (mm) cumulative sieve residual (%)									Fineness modulus
9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	<0.075	
0	4	29	46	59	68	72	87	100	2.6

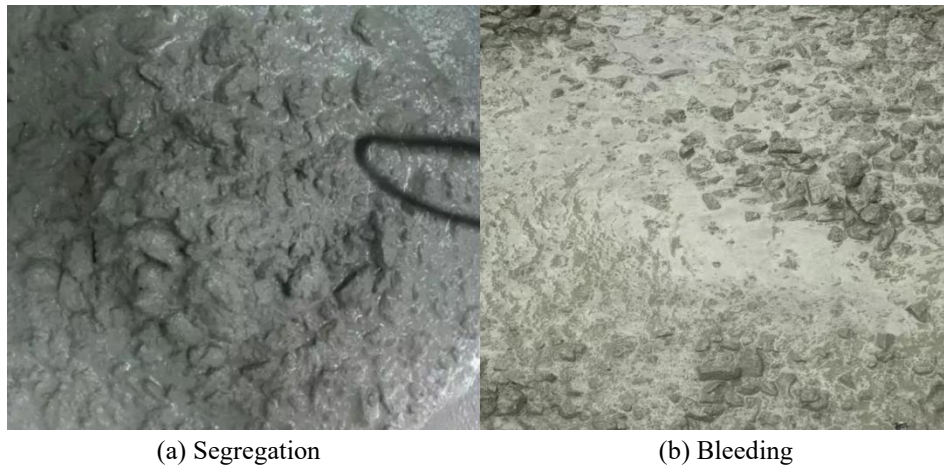
Table 7. Grading of the Stone Chip

Gradation type	The following particle size (mm) cumulative sieve residual (%)						Fineness modulus
	4.75	2.36	1.18	0.6	0.3	0.15	
J1	1	3	10	41	70	90	2.1
J2	3	7	20	49	76	84	2.3
J3	5	13	29	54	79	93	2.6
J4	7	19	40	63	90	91	2.9
J5	8	25	49	70	92	94	3.2
J6	3	37	54	72	84	88	3.3

4. Effect of Stone Chip Fineness Modulus on Concrete Technical Properties

4.1 Construction Workability

Segregation is the separation of coarse aggregates and mortar in the concrete mix (Figure 4(a)), whereas bleeding occurs when water rises and coarse aggregates sink in the concrete mix (Figure 4(b)). Table 8 lists the test results of the effects of the stone chip fineness modulus on the construction workability of stone chip concrete.



(a) Segregation (b) Bleeding
Figure 4. Concrete Segregation and Bleeding Phenomenon

Table 8. Test Results on the Effect of Stone Chip Fineness Modulus on the Construction Workability of Stone Chip Concrete

Concrete strength grade	Fineness modulus	Slump (mm)	Segregation situation	Bleeding situation
C30	2.1	80	Basically nothing	Basically nothing
	2.3	85	Basically nothing	Basically nothing
	2.6	170	Basically nothing	Basically nothing
	2.9	210	Slight	Slight
	3.2	220	Slight	Serious
	3.3	170	Serious	Serious
C40	2.1	80	Basically nothing	Basically nothing
	2.3	90	Basically nothing	Basically nothing
	2.6	165	Basically nothing	Basically nothing
	2.9	200	Slight	Slight
	3.2	215	Serious	Slight

C50	3.3	210	Serious	Serious
	2.3	200	Basically nothing	Basically nothing
	2.6	215	Basically nothing	Basically nothing
	2.9	220	Basically nothing	Basically nothing
	3.2	225	Slight	Slight
	3.3	230	Slight	Serious
	2.3	220	Serious	Serious

As shown in Table 8, the slump of stone chip concrete with different strength grades increases as the fineness modulus increases; hence, the construction workability of concrete with different strengths formulated by stone chips with a higher fineness modulus can be maintained in a better state. Segregation and bleeding of the J6 gradation were severe, mostly due to the absence of fine material resulting from the separation of cement paste from the mixture. Due to the greater specific surface area of fine sand, achieving the fluidity requirements for C30 and C40 stone chip concrete was difficult when the fine aggregate was fine sand. The increase in specific surface area necessitates more cement slurry to lubricate the aggregates, and the increase in coarse particles in the sand enhances the fluidity of the concrete mix when cement, water, and aggregates are combined (Zhu et al., 2025). Due to the addition of high-efficiency water-reducing agents, the concrete slump at different fineness modulus can be met for C50 stone chip concrete. However, this causes the stone chip surface to release a large amount of water, making it difficult to maintain the mix's stability and prone to bleeding, segregation, and workability degradation. Due to the larger specific surface area of the particles necessitating a greater cement paste package, the increase in the particle size of stone chips makes concrete more susceptible to segregation and bleeding. In addition, coarse particles are more likely to move along the slope than fine particles and tend to separate from the mixture (Pan et al., 2025).

In summary, the fineness modulus of stone chips is an important influencing factor for the construction workability of stone chip concrete, and even if poor gradation can be made to meet the construction requirements through admixtures and other means, the admixtures will cause the release of a large amount of water on the stone chip surface, making it difficult to maintain the stability of the mix and prone to bleeding, segregation, and workability degradation. Because concrete is more susceptible to segregation and bleeding as the particle size of stone chips grows, the fineness modulus of stone chips should not be very high. Therefore, the fineness modulus of stone chips should not exceed 3.2 when considering only the construction workability of concrete.

4.2 Mechanical Properties

Figure 5 shows the effects of stone chips with different fineness modulus on the mechanical properties of stone chip concrete.

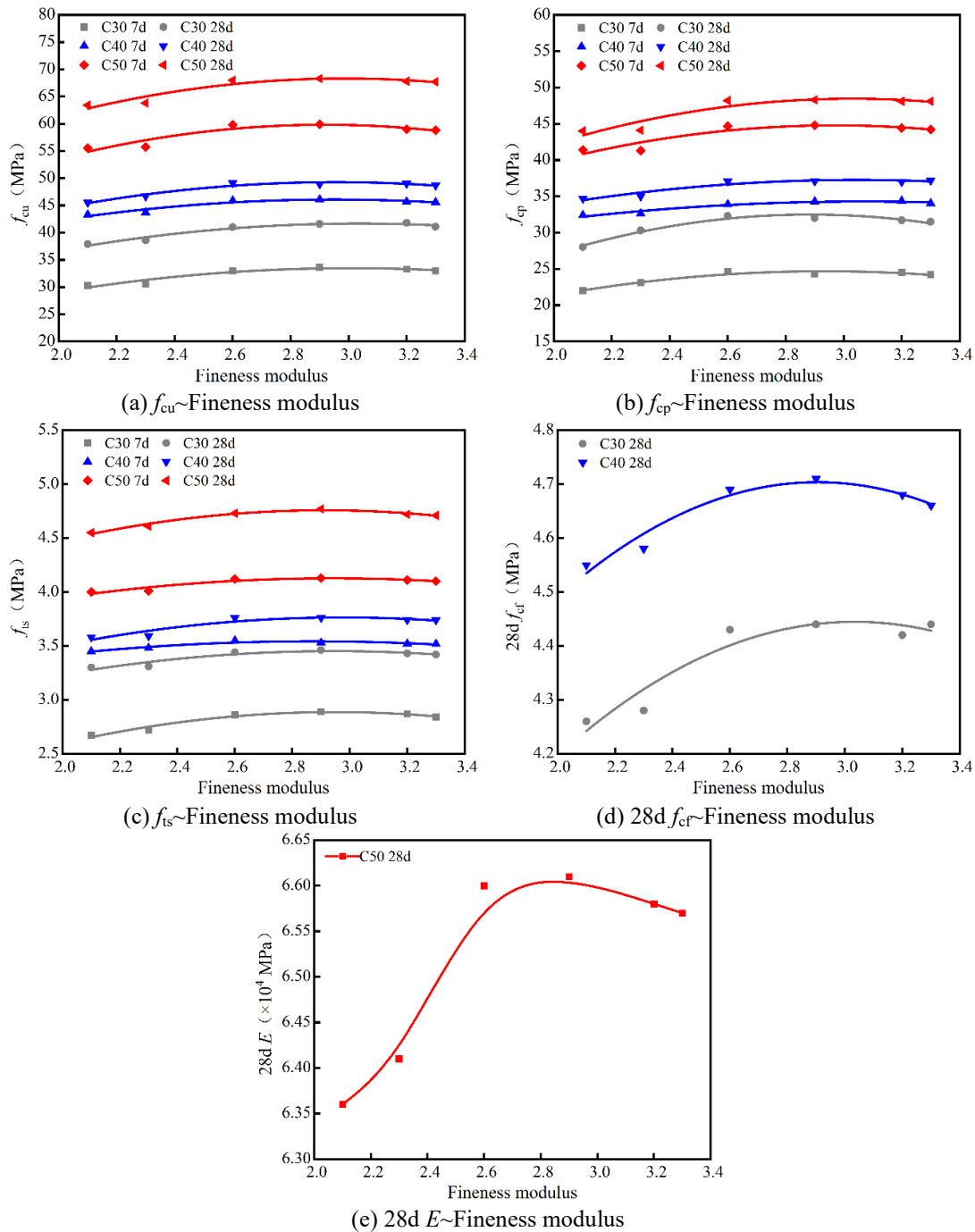


Figure 5. Relationship between Fineness Modulus and Mechanical Properties of Stone Chip Concrete

As illustrated in Figure 5, the mechanical strength of concrete prepared with different fineness modulus of stone chips changed with gradation, and as the fineness modulus of stone chips increased, all mechanical strength indices of concrete tended to first increase and then decrease. When the fineness modulus of the stone chips was less than 2.6, all mechanical strength indices of concrete increased as the fineness modulus increased. Notably, compared with the fineness modulus of 2.1, the 7d and 28d f_{cu} of C30 concrete with a fineness modulus of 2.6 increased by 8.9% and 8.2%, the 7d and 28d f_{cp} increased

by 10.5% and 14.3%, and the 7d and 28d f_{ts} increased by 7.1% and 4.2%, respectively; the 28d f_{cf} increased by 4.0%. For the C40 concrete with a fineness modulus of 2.6, the 7d and 28d f_{cu} increased by 6.0% and 7.9%, the 7d and 28d f_{cp} increased by 4.6% and 6.9%, and the 7d and 28d f_{ts} increased by 2.9% and 5.0%, respectively, the 28d f_{cf} increased by 3.1%. Regarding the C50 concrete with a fineness modulus of 2.6, the 7d and 28d f_{cu} increased by 7.7% and 7.3%, the 7d and 28d f_{cp} increased by 8.0% and 9.5%, and the 7d and 28d f_{ts} increased by 3.0% and 4.0%, respectively; the 28d E increased by 3.8%. Furthermore, compared with the fineness modulus of 2.3, the 7d and 28d f_{cu} of C30 concrete with a fineness modulus of 2.6 increased by 7.8% and 6.2%, 7d and 28d f_{cp} increased by 5.2% and 5.6%, and 7d and 28d f_{cf} increased by 5.1% and 3.9%, respectively; the 28d f_{cf} increased by 3.5%. For the C40 concrete with a fineness modulus of 2.6, the 7d and 28d f_{cu} increased by 5.0% and 5.1%, the 7d and 28d f_{cp} increased by 4.0% and 6.0%, and the 7d and 28d f_{cf} increased by 2.0% and 4.7%, respectively; the 28d f_{cf} increased by 2.4%. Regarding the C50 concrete with a fineness modulus of 2.6, the 7d and 28d f_{cu} increased by 7.4% and 6.6%, the 7d and 28d f_{cp} increased by 8.2% and 9.3%, and the 7d and 28d f_{cf} increased by 2.7% and 2.6%, respectively; the 28d E increased by 3.0%. When the fineness modulus was between 2.6 and 3.3, the effect of the stone chip fineness modulus on the mechanical strength of concrete was not significant and was thought to have no substantial effect on the concrete performance index, considering the test error. Due to the increased specific surface area of fine aggregates, the mechanical strength of concrete decreased as the fineness modulus of the stone chips decreased. A lesser fineness modulus implies a larger specific surface area of aggregates, and an increase in fineness leads to a drop in concrete compactness, which leads to a decrease in mechanical strength. Therefore, when considering only the mechanical strength of concrete, the fineness modulus of the stone chips should be 2.6 or higher.

4.3 Durability

4.3.1 Permeability Resistance

The infiltration depth pattern of concrete formulated with stone chips of different fineness modulus at a seepage pressure of 1.2 MPa is shown in Figure 6.

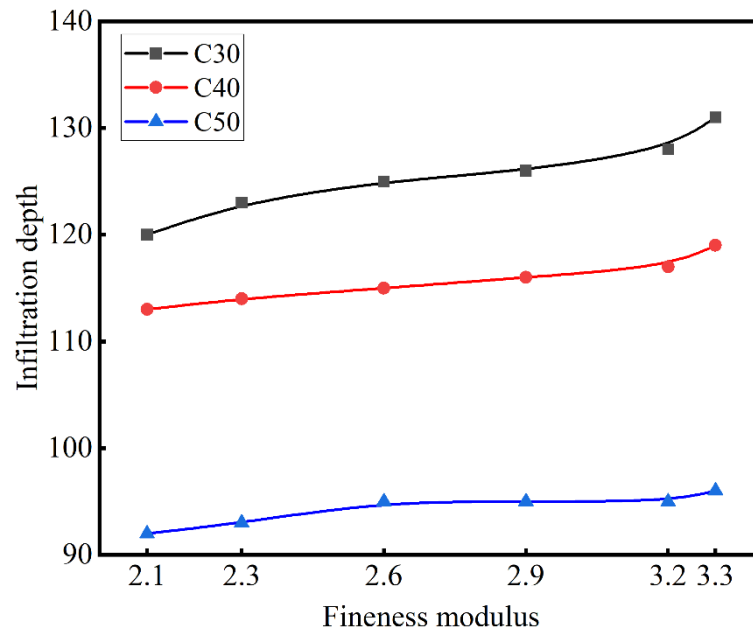
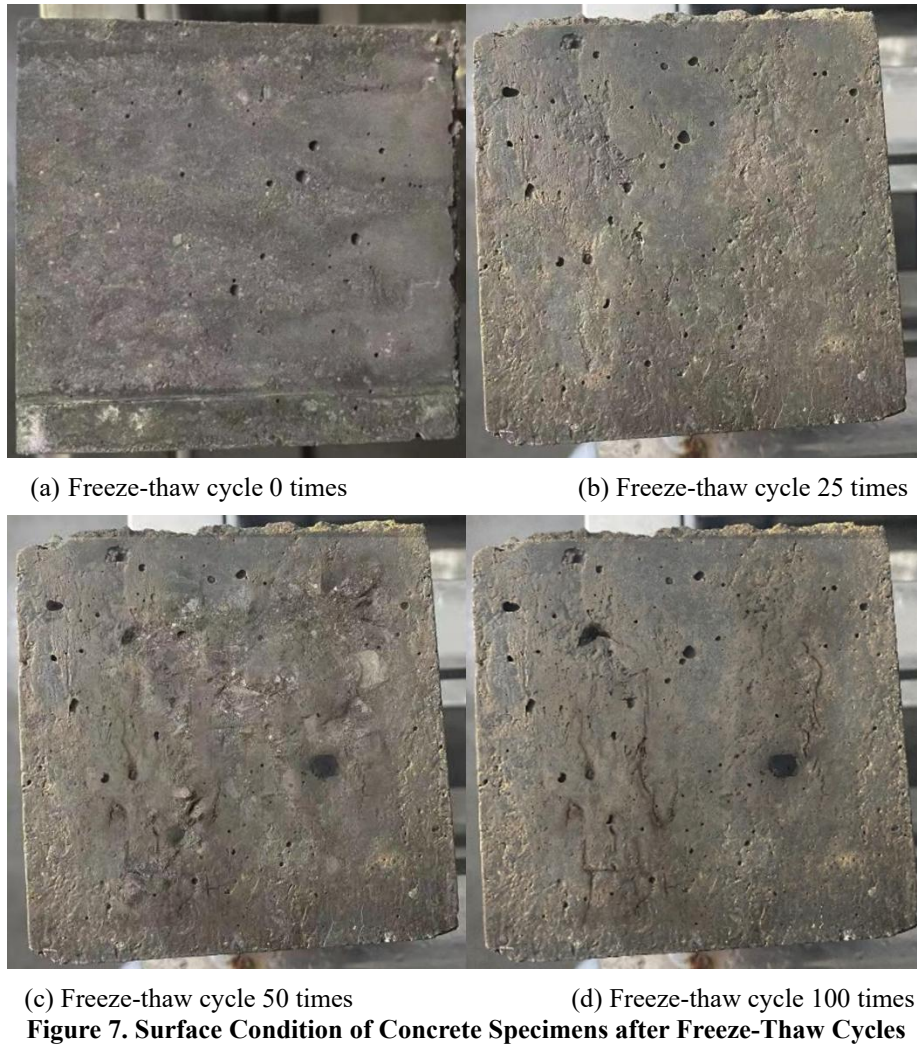


Figure 6. Infiltration Depth of Stone Chip Concrete with Different Fineness Modulus

As illustrated in Figure 6, under a water pressure of 1.2 MPa, the stone chip concrete specimens of different strength levels do not appear to be seeping at the top, and as the fineness modulus increases, so does the infiltration depth of the stone chip concrete. The greater the ease of fluid migration within the concrete, the less permeable the concrete becomes. This indicates that more pores exist at the slurry–aggregate interface in the concrete cement slurry prepared by the stone debris with a high detail modulus, and the stone debris with a large specific surface area needs more cement slurry to be wrapped, resulting in increased pores (Wang et al., 2023). This means that to ensure the workability and strength of stone chip concrete, selecting stone chips with a smaller fineness modulus would aid in improving concrete impermeability. Therefore, when considering the permeability resistance of concrete, the fineness modulus of stone chips should not exceed 3.2.

4.3.2 Freezing Resistance

The test results of the effect of the stone chip fineness modulus on concrete freezing resistance are shown in Table 9, and the surface condition of concrete specimens after freeze-thawing is shown in Figure 7. C30-2.1 represents C30 concrete with a stone chip fineness modulus of 2.1.



As illustrated in Figure 7, before the freeze-thaw cycle began, the surface of the $100 \times 100 \times 100$ mm concrete test block soaked in $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ water for 4 days and nights was relatively smooth, with a few bubbles and no obvious lines. After 25 cycles of freezing and thawing, the surface of the concrete test block exhibited lines of concrete shrinkage; nonetheless, the test block did not crack, and the bubbles and pores grew larger. After 50 cycles of freezing and thawing, the test block's surface developed visible cracks, the pores grew larger, and the cement paste on the surface of the rubble peeled slightly. After 100 cycles of freezing and thawing, cracks developed into blocks of concrete falling off from the surface of the specimen, and a little concrete aggregate was observed.

Table 9. Effect of Stone Chip Fineness Modulus on Concrete Freezing Resistance

Concrete Type	m and f_{cu} of stone chip concrete after different number of freeze-thaw cycles							
	m (g)				f_{cu} (Mpa)			
	0	25	50	100	0	25	50	100
C30-2.1	2521	2530	2539	2505	37.9	35.5	30.5	23.8
C30-2.3	2531	2539	2548	2513	38.6	36.2	30.8	24.0
C30-2.6	2533	2540	2549	2515	41.0	38.3	32.6	25.1
C30-2.9	2520	2527	2535	2501	41.6	38.9	32.9	25.5
C30-3.2	2550	2556	2562	2529	41.8	39.0	32.7	25.1
C30-3.3	2527	2532	2538	2506	41.1	38.3	31.7	24.6
C40-2.1	2542	2553	2556	2525	45.5	42.7	36.3	28.7
C40-2.3	2530	2541	2543	2513	46.7	43.7	37.1	29.0
C40-2.6	2522	2531	2533	2504	49.1	45.9	38.9	30.2
C40-2.9	2554	2562	2565	2536	48.9	45.7	38.6	29.9
C40-3.2	2541	2549	2550	2522	49.0	45.8	38.5	29.8
C40-3.3	2531	2539	2539	2511	48.7	45.4	37.7	29.0
C50-2.1	2549	2560	2563	2531	63.4	60.6	56.5	45.6
C50-2.3	2522	2533	2535	2504	63.8	60.9	56.7	45.6
C50-2.6	2533	2544	2544	2514	68.0	64.9	60.2	48.4
C50-2.9	2549	2559	2560	2528	68.3	65.2	60.1	48.4
C50-3.2	2555	2564	2564	2534	67.8	64.6	59.4	47.9
C50-3.3	2521	2529	2529	2500	67.7	64.2	58.9	47.7

The mass loss rate and cubic compressive strength loss rate of concrete specimens were calculated according to Eqs. (3) and (4), respectively, and then the deterioration curves of the freezing test of stone chip concrete with different fineness modulus were plotted (Figures. 8-10).

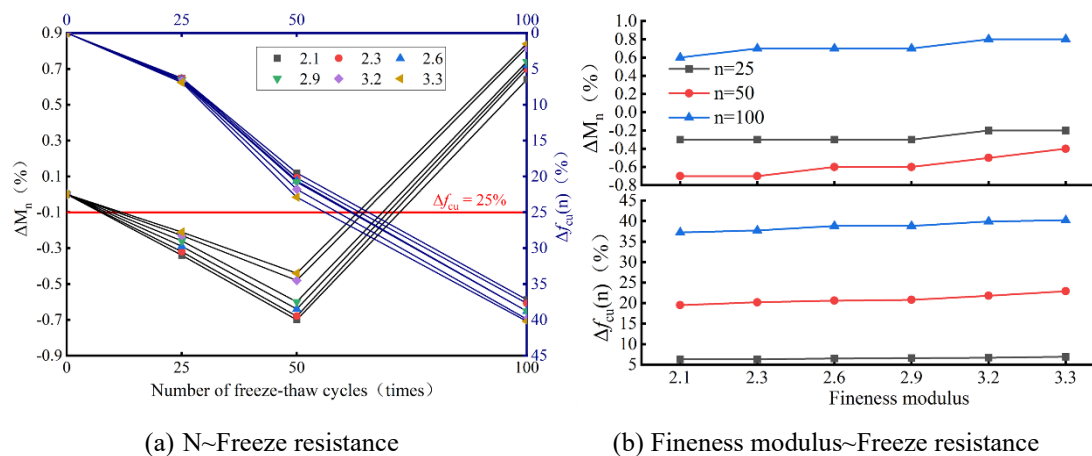
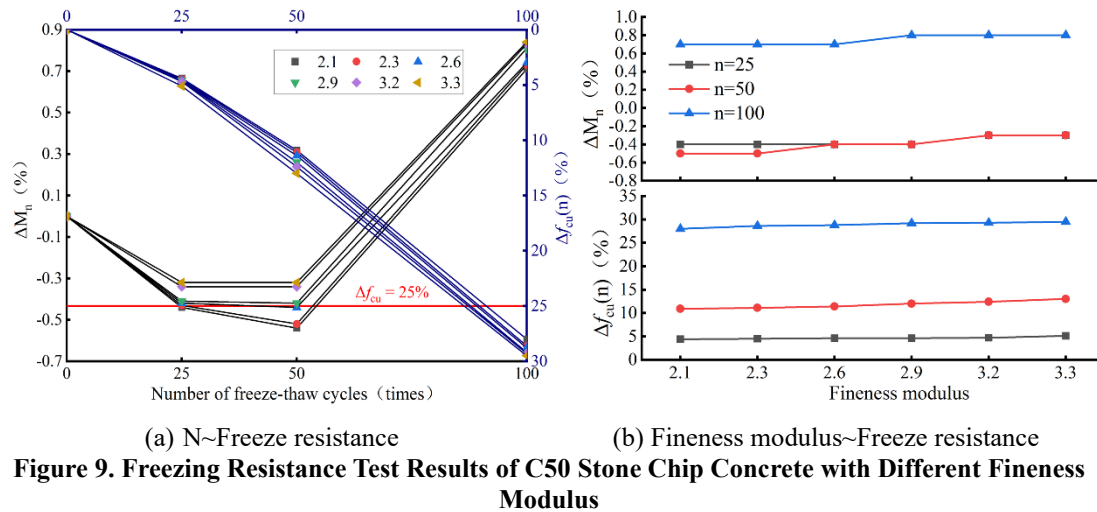
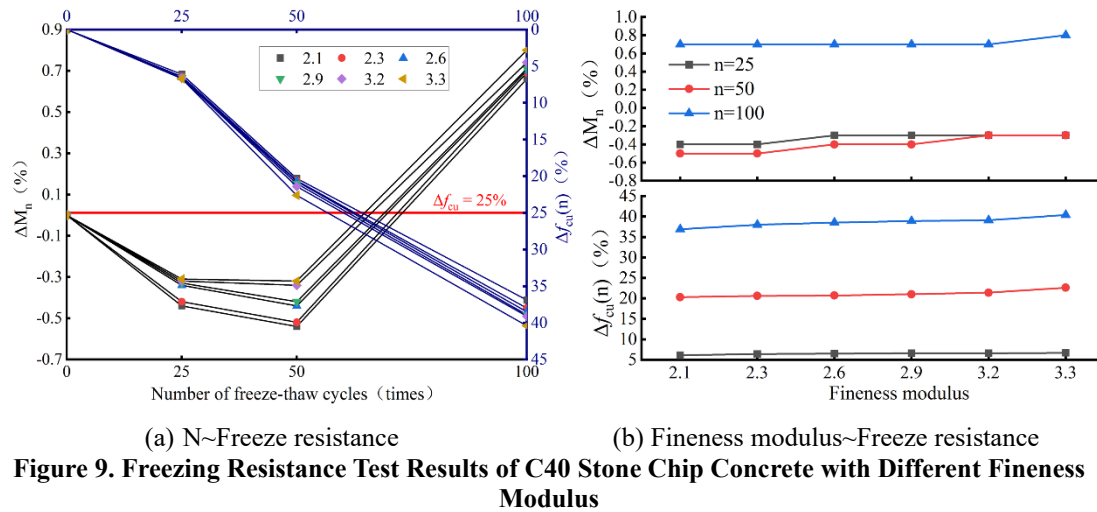


Figure 8. Freezing Resistance Test Results of C30 Stone Chip Concrete with Different Fineness Modulus



As shown in Figures 8–10, stone chip concrete with different fineness modulus met the freezing resistance grade standard. When the cube compressive strength loss rate of stone chip concrete exceeded 25%, as specified in the specification, the mass loss rate did not exceed 5%, indicating that the specification is somewhat broad for the mass loss rate of concrete after freeze-thaw cycles. As the number of freeze-thaw cycles increased, the mass of stone chip concrete first increased and then decreased. After 50 cycles, the mass loss rate was the lowest. As the cycle proceeded, the specimen's mass loss continued to increase at an ever-accelerating rate. This effect occurred for the following reasons: for the specimens in the freeze-thaw test process, freezing expansion through the concrete internal pore structure increased its water absorption rate, and water absorption led to an increase in mass greater than the mass of the aggregate surface spalling mortar; however, as the freeze-thaw cycle progressed, the mass of the aggregate surface spalling mortar gradually exceeded the mass of the concrete water absorption, resulting in a decreased overall quality of concrete. After the freeze-thaw cycle, the mass and strength loss rate of concrete made with stone chips with a lower fineness modulus was substantially reduced, indicating its

superior frost resistance ability. This effect occurred because concrete with a higher fineness modulus is prone to segregation, resulting in specimens with coarse aggregates located near the concrete surface during the formation. According to Pigeon M, large particles of aggregates are more susceptible to freezing damage (Xu et al., 2020). Therefore, choosing stone chips with a small fineness modulus can improve the frost resistance of concrete while maintaining the construction and mechanical strength of stone chip concrete.

5. Exploring the Reasonable Range of Stone Chip Fineness Modulus

Stone quarries produce many stone chips as waste—a great burden on the surrounding environment. Owing to the shortage of natural river sand in recent years, replacing some river sand with concrete has become a trend. However, the specification for the technical standards of the mechanism sand is too broad, and using its provisions for the range of stone chip grading would result in significant differences in the technical properties of the prepared concrete, making quality difficult to guarantee. Therefore, determining a reasonable range of stone chip fineness modulus is particularly important. Based on this, this study investigates the influence of the fineness modulus of stone chips on the performance of the concrete prepared and concludes that the fineness modulus of stone chips should be less than 3.2 from the perspective of the construction and ease of concrete, it should exceed 2.6 from the perspective of the mechanical properties of concrete, and smaller fineness modulus of stone chips should be used from the perspective of the durability of concrete. In summary, the recommended range of stone chip fineness modulus is 2.6–3.2. The stone chips in this range can ensure concrete compactness while improving the prepared concrete strength and durability. In addition, the stone chips have a relatively reasonable specific surface area, so the amount of mortar required to prepare concrete is also within an acceptable range, and the concrete has good construction workability.

6. Conclusion

The range of the stone chip fineness modulus is broad, the grading is unreasonable, and the aggregate screen residuals frequently exhibit U-shaped distributions, with large values at both ends and tiny values in the middle. Therefore, to provide a suitable stone chip fineness modulus range, its influence on construction workability, mechanical properties, and durability of concrete construction was studied. This study's findings are summarized below.

- (1) Although concrete prepared from poorly graded stone chips can meet construction requirements when admixtures and other means are used to make its slump, segregation, bleeding, and deterioration of workability are likely to occur. Therefore, the fineness modulus of stone chips should not exceed 3.2 when considering the construction workability of concrete.
- (2) The mechanical strength of each concrete formulated with different fineness modulus of stone chips varies with grading; as the fineness modulus of stone chips increases, the mechanical strength indices of

concrete tend to first increase and then decrease; considering the test error, fineness modulus exceeding 2.6 are thought to have no significant effect on the concrete performance index.

(3) Although concrete formulated with different fineness modulus stone chips can meet the specification requirements for permeability and freezing resistance, selecting stone chips with smaller fineness modulus favors the improvement of concrete permeability and freezing resistance.

(4) Considering the construction workability, mechanical properties, and durability of concrete mixture, the fineness modulus of stone chips should be maintained between 2.6 and 3.2.

Various types of lithologies are widely distributed around the world, and stone chips, as engineering materials, are often gathered locally and not transported over long distances. Therefore, to make the effect law of the stone chip fineness modulus on concrete performance universal, the next stage is to conduct research on the effect of stone chips of various parent rock lithologies on concrete performance.

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References

- Aboagye, B., et al. (2025). Influence of manufactured sand on concrete properties: a review. *Canadian Journal of Civil Engineering*, 53. <https://doi.org/10.1139/cjce-2025-0243>
- Da, S., et al. (2022). Sand mining: Stopping the grind of unregulated supply chains. *The Extractive Industries and Society*, 10, 101070. <https://doi.org/10.1016/j.exis.2022.101070>
- Dudka, S., & Adriano, D. C. (1997). Environmental impacts of metal ore mining and processing: a review. *Journal of Environmental Quality*, 26(3). <https://doi.org/10.2134/jeq1997.00472425002600030003x>
- Hashim, R., et al. (2011). Characterization of raw materials and manufactured binderless particleboard from oil palm biomass. *Materials & Design*, 32(1), 246-254. <https://doi.org/10.1016/j.matdes.2010.05.059>
- Hor, Y., et al. (2017). Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete. *Construction and Building Materials*, 155(nov.30), 463-474. <https://doi.org/10.1016/j.conbuildmat.2017.08.077>
- Li, H., et al. (2021). Effect of different lithological stone powders on properties of cementitious materials. *Journal of Cleaner Production*, 289, 125820. <https://doi.org/10.1016/j.jclepro.2021.125820>
- Nikzad, Y., et al. (2024). Effect of sand fineness modulus on SCC and SCLC properties. *Construction and Building Materials*, 421, 135761. <https://doi.org/10.1016/j.conbuildmat.2024.135761>

- Pan, J., et al. (2021). Influence of rheological behavior of mortar matrix on fresh concrete segregation and bleeding. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 45, 1281-1295. <https://doi.org/10.1007/s40996-020-00450-5>
- Qian, K., et al. (2026). The shrinkage and durability of concrete prepared with waste rock manufactured sand. *Case Studies in Construction Materials*, 24, e05699. <https://doi.org/10.1016/j.cscm.2025.e05699>
- Ruan, Y., et al. (2024). Experimental study on the strength and durability of manufactured sand HPC in the Dalian Bay undersea immersed tube tunnel and its engineering application. *Materials*, 17(20), 5003. <https://doi.org/10.3390/ma17205003>
- Shang, Y., et al. (2004). A case history of tunnel boring machine jamming in an inter-layer shear zone at the yellow river diversion project in China. *Engineering Geology*, 71(3-4), 199-211. [https://doi.org/10.1016/S0013-7952\(03\)00134-0](https://doi.org/10.1016/S0013-7952(03)00134-0)
- Shen, W., et al. (2022). Cleaner production of high-quality manufactured sand and ecological utilization of recycled stone powder in concrete. *Journal of Cleaner Production*, 375, 134146. <https://doi.org/10.1016/j.jclepro.2022.134146>
- Troisi, G., et al. (2016). Impacts of oil spills on seabirds: unsustainable impacts of non-renewable energy. *International Journal of Hydrogen Energy*, 41(37), 16549-16555. <https://doi.org/10.1016/j.ijhydene.2016.04.011>
- Xu, G., et al. (2020). Influence of size and surface condition of distributing-filling coarse aggregate on the properties of aggregate-interlocking concrete. *Construction and Building Materials*, 261, 120002. <https://doi.org/10.1016/j.conbuildmat.2020.120002>
- Wang, J., et al. (2023). Study of early-age hydration, mechanical properties development, and microstructure evolution of manufactured sand concrete mixed with granite stone powder. *Materials*, 16(13), 4857. <https://doi.org/10.3390/ma16134857>
- Zheng, S., et al. (2023). Effects of fines content on durability of high-strength manufactured sand concrete. *Materials*, 16(2), 522. <https://doi.org/10.3390/ma16020522>
- Zhu, X., et al. (2023). Research on carbon emission reduction of manufactured sand concrete based on compressive strength. *Construction and Building Materials*, 403, 133101. <https://doi.org/10.1016/j.conbuildmat.2023.133101>
- Zhu, J., et al. (2025). Unifying viscosity of cement-based materials made with manufactured sand. *Construction and Building Materials*, 458, 139677. <https://doi.org/10.1016/j.conbuildmat.2024.139677>