Fang *et al. Int J Concr Struct Mater (2025) 19:41*
https://doi.org/10.1186/s40069-025-00784-2

International Journal of Concrete Structures and Materials

REVIEW **Open Access**

Characteristics of Iron Ore Tailings Sand and Properties of Iron Ore Tailings Sand Concrete: A Review

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Abstract

As a common industrial solid waste, iron ore tailing sand (IOTS) has a large amount of storage, and the treatment efficiency is unsatisfactory. Scientific and reasonable incorporation of IOTS waste into concrete is one of the critical ways to realize bulk utilization and sustainable development. This paper first summarizes the basic material characteristics of IOTS, and the similarities and differences between IOTS and natural sand (NS) are compared and analyzed. Followed with a presentation of research findings on properties of IOTS concrete with respect to mix ratio, workability, mechanical properties, drying shrinkage and durability. Subsequently, the mechanical behaviors of IOTS concrete members are analyzed and summarized in terms of experimental research, theoretical analysis and numerical simulation. Eventually, the future research directions of material and component levels of IOTS concrete are reasonably prospected. These conclusions may inform the sustainable technical application of IOTS in concrete.

Keywords Iron ore tailings sand, Concrete, Material properties, Drying shrinkage, Mechanical behavior, Durability

1 Introduction

In China, iron ore resources are abundant and widely distributed, while most of them fall into lean iron ore with low iron content and complex iron ore types (Li et al., 2014; Qin et al., 2024). Influenced by the level of beneficiation, ore grade and mining costs, the current mining efficiency of iron ore is unsatisfactory, and numerous iron ore tailings are inevitably produced in mining and beneficiation process (Gyllenram et al., 2021; Rao et al., 2023). Due to the limited level of existing technology, part of iron ore tailings are not well disposed and recycled, while simply abandoned as tailings (Yellishetty and Mudd, 2014; Sun et al., 2020). Large quantity of iron ore tailings not only occupy land, waste resources, but also pollute air, water and soil, which seriously affect the ecological environment (Galvão et al., 2018; Li et al., 2024; Yang et al., 2023; Zhang et al., 2021). Therefore, how to scientifically recycle waste iron ore tailings on a large scale and effectively reduce accumulation has become a hot issue in research.

With the increase of infrastructure construction, the consumption of concrete is increasing continually, the demand for natural sand (NS) is huge, and the shortage of NS resources is also becoming increasingly prominent. Therefore, the search for suitable replacement materials for NS is imminent. IOTS is an industrial waste produced by crushing and magnetic separation of the raw ores, which is quite different from NS formed under natural conditions (Tang et al., 2019a, 2019b; Zhou et al., 2023). However, it has been shown that after reasonable screening and proper treatment, IOTS can completely or partially substitute NS as fine

Journal information: ISSN 1976-0485/eISSN 2234-1315.

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aggregate for the production of commercial concrete (Zhao et al., 2021b; Protasio et al., 2021; Qiu et al., 2023).

Recently, scholars have performed a series of experimental, theoretical and numerical simulation studies on workability (Radlinski and Olek, 2015; Li et al., 2023; Shi et al., 2024a, 2024b), mechanical properties (Cheng et al., 2016; Wang and Liu 2019; Zhang et al., 2013), drying shrinkage (Jia et al., 2013; Zhang et al., 2024; Shi et al., 2024a, 2024b) and durability (Li et al., 2020; Thomas et al., 2013; Wang et al., 2019) of IOTS concrete, and have achieved considerable results. Meanwhile, the promulgation of "Technical code for application of IOTS sand concrete" (GB 51032, 2014) fully confirms the application values of IOTS and the feasibility of IOTS concrete application in engineering from the level of national specification. Resourceful application of IOTS concrete can not only solve the problems of IOTS stockpiling, occupying large quantity of land and polluting the environment, but also alleviate the prominent contradiction of the increasing shortage of NS resources and reduce the cost of project, which is in line with the needs of environmental protection and sustainable development, with significant social and economic benefits.

In this study, the basic material characteristics of IOTS are summarized from the aspects of physical properties, mineral compositions, and similarities and differences between IOTS and NS are analyzed and compared. The feasibility of IOTS replacing NS in preparing concrete is discussed. Subsequently, the research progress and engineering application of IOTS concrete are summarized in terms of mix ratio, workability, mechanical properties, drying shrinkage and durability, the problems existing in current researches are addressed, and the future research directions are envisioned. Furthermore, the mechanical behaviors, such as compression, flexural and shear of IOTS concrete members are analyzed and summarized, laying the foundation for large-scale application of IOTS concrete members in engineering.

2 Basic Material Characteristics of IOTS

2.1 Physical Properties

As suggested in Chinese code (GB/T 31288–2014), IOTS is the waste aggregate with particle size lower than 4.75 mm resulting from fine grinding and separation of iron ores. Depending on fineness modulus, IOTS can be broadly categorized into fine sand (fineness modulus of 1.6 to 2.2) and ultra-fine sand (fineness modulus of 0.7 to 1.5). Detailed restrictions are made on the particle gradation of IOTS used in concrete (Table 1), the content of stone powder and mud (Table 2), the content of hazardous substances (Table 3), and the content of sulphides and sulphates (not more than 0.5% by mass of SO_3) in Chinese code (GB51032–2014). Meanwhile, American standard (ASTMC33/C33M-2018) and British Standard (EN, 12620–2008) also impose corresponding requirements for the use of IOTS as concrete aggregates.

IOTS is quite different from NS formed under natural conditions. Fig. 1 shows the SEM images of NS and IOTS (Zhao et al., 2014). The surface of IOTS is rough and angular due to repeated mechanical impact and crushing, while the surface of NS is relatively smooth after weathering, water impact and other long-term effects. In contrast, the internal friction between IOTS particles is greater than that of NS. Due to multiple crushing, the particles of IOTS contain more fine components, most of which fall into fine or ultra-fine sand, while NS exhibits relatively uniform particle size distribution after natural weathering and transportation, as depicted in Fig. 2 (Zhao et al., 2014). Thus, the specific surface area of NS is much smaller than that of IOTS.

Table 1 The particle gradation of IOTS

The nominal diameter of the sieve (mm)	IOTS	
	Fine sand	Ultra-fine
Square screen hole	Accumulated screen residue (%)	
4.75 mm	10 ~ 0	0
2.36 mm	15 ~ 0	15 ~ 0
1.18 mm	25 ~ 0	20 ~ 0
600 μm	40 ~ 16	25 ~ 0
300 μm	85 ~ 55	55 ~ 20
150 μm	94 ~ 74	90 ~ 30

Table 2 The content of stone power and mud in IOTS (%)

Item		Index
Stone power content	*MB* ≤ 1.4 or Rapid test qualified	≤15.0
	MB > 1.4 or Rapid test failed	≤5.0
Mud content		≤1.0

MB the measured value of methylene blue in manufactured sand

Table 3 The limit of hazardous substances in IOTS

Item	Index
Mica (by mass)	≤2.0
Light substance (by mass)	≤1.0
Organics	qualified
Chloride (in terms of mass of chloride ions)	≤ 0.02

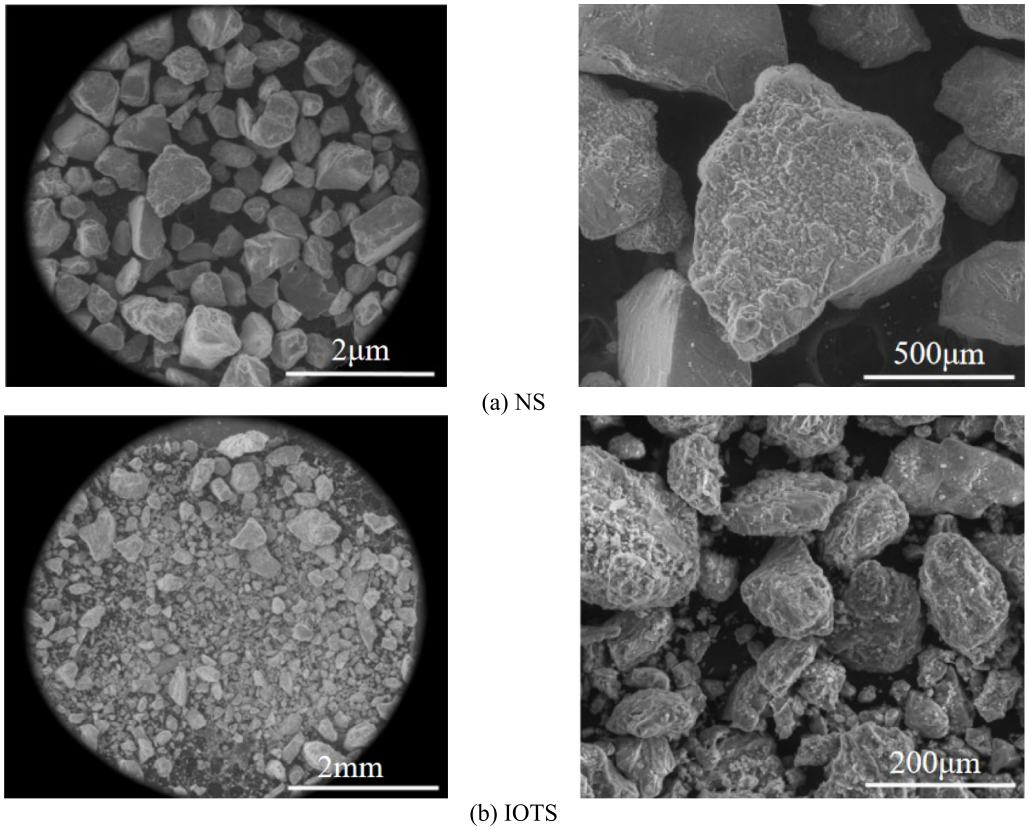


Fig. 1 SEM images of NS and IOTS (Zhao et al., 2014)

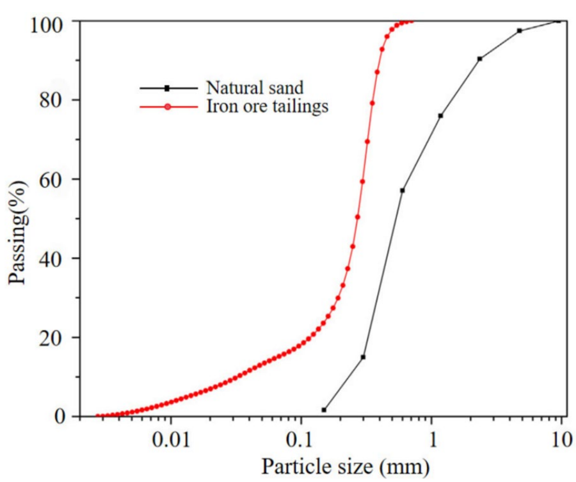


Fig. 2 Particle size distribution of NS and IOTS (Zhao et al., 2014)

Additionally, the physical properties of IOTS and NS are compared in Table 4. It can be concluded that there is a strong correlation between fineness modulus of IOTS and NS with respect to the source, while the differences in other properties are less pronounced. Generally, the apparent density of IOTS is greater than that of NS, and its porosity and water absorption are also greater than those of NS.

2.2 Mineral Composition

NS is mostly composed of weathered rock, mainly siliceous or calcareous minerals, with relatively homogeneous composition, whereas the IOTS often contains a variety of compounds in its composition, with major crystalline phases, such as albite, quartz, diopside and clinochlore, as illustrated in Fig. 3 (Zhao et al., 2014). Table 5 lists the chemical composition of IOTS from different sources. Apparently, the chemical composition of IOTS from different sources varies, but their main components are similar, including SiO_2, Fe_2O_3 and Al_2O_3. Statistically most IOTS has the highest content of SiO_2, followed by Fe_2O_3.

3 IOTS Concrete

IOTS concrete is a new type of green concrete material that utilizes IOTS waste instead of NS as fine aggregate. Rational use of IOTS not only solves problem of scarcity of NS resources, but also exhibits remarkable social, economic and environmental benefits. Currently, scholars have conducted a range of experimental and theoretical

Table 4 Physical properties of IOTS and natural sand (NS)

Ref.	Region	Fine aggregate	Fineness modulus	Apparent density	Water absorption /%	Porosity /%
Shettima et al., 2016	Malaysian Peninsula	IOTS	1.05	–	7.0	–
Jayasimha et al., 2022	Bellari	IOTS	2.98	2.80	1.0	–
		NS	2.55	–	1.75	–
Chen et al., 2017	Liaoning	IOTS	1.58	2.82	–	–
		NS	2.84	2.76	–	–
Xie et al., 2022	Hebei	IOTS	2.4	2.88	2.54	–
Chinnappa et al., 2020	India	IOTS	–	3.31	2.29	50
		NS		2.70	0.10	47
Bian et al., 2008	Beijing	IOTS	1.3	3.09	–	33.1
		NS	3.2	2.60	–	30.0
Feng et al., 2013a, 2013b	Qianxi	IOTS	2.5	2.83	–	45
		NS	2.7	2.73	6.4	40
Feng et al., 2013a, 2013b	Zunhua	IOTS	2.8	2.78	–	44
Wang et al., 2017	Shanxi	IOTS	2.7	2.64	5.8	–
		NS	2.4	2.60	3.6	–
Yang et al., 2014	Jiangsu	IOTS	–	3.11	–	–
Zhao et al., 2023	Tangshan	IOTS	0.9	2.88	8.12	–
		NS	2.59	2.73	3.54	–
Duarte et al., 2022	Brazil	IOTS	–	1.16	–	8.20
Yin et al., 2019	Shanxi	IOTS	2.6	3.03	–	–
		NS	3.0	2.68	–	–

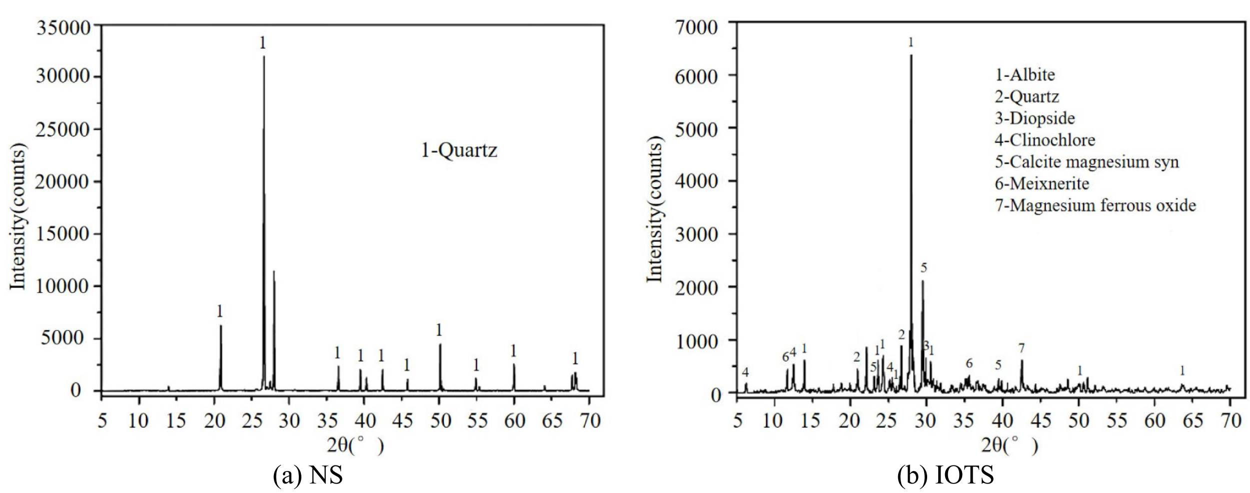


Fig. 3 XRD patters of NS and IOTS (Zhao et al., 2014)

studies on mix ratio, workability, mechanical properties, drying shrinkage and durability of IOTS concrete, and have obtained considerable achievements.

3.1 Mix Ratio

In terms of mix ratio studies, the mechanical properties of concrete under mix ratios of 0%, 25%, 50%, 75% and 100% IOTS content were investigated, finding that concrete strength increased as IOTS content increased and then decreased, and the recommended optimal IOTS content was 25% (Shettima et al., 2016). Subsequently, a comparable study was conducted and it was indicated that the incorporation of IOTS was favorable on the workability and mechanical properties of concrete when

Table 5 Chemical composition of IOTS from different sources by mass (%)

Ref.	Region	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	SO_3	Na_2O	TiO_2
Shettima et al., 2016	Malaysia	56	8.30	10	4.30	–	1.50	–	–	–
Jayasimha et al., 2022	Bellari	34.65	0.12	28.65	28.42	5.7	0.249	–	0.441	–
Chen et al., 2017	Liaoning	54.4	9.26	5.65	3.78	2.98	1.37	–	0.87	0.43
Xie et al., 2022	Hebei	58.70	11.10	14.40	4.30	3.80	3.80	0.10	0.20	–
Chinnappa et al., 2020	India	49.75	27.03	9.74	4.06	3.11	0.50	–	–	–
Bian et al., 2008	Beijing	59.3	4.3	13.5	2	1.7	–	5.9	1.5	–
Feng et al., 2013a, 2013b	Qianxi	70.27	7.04	8.43	3.92	3.03	2.62	2.02	1.66	–
Feng et al., 2013a, 2013b	Zunhua	58.76	10.41	11.84	5.14	6.11	1.62	0.10	2.71	–
Wang et al., 2017	Shanxi	68.79	11.63	6.57	2.96	3.05	1.21	0.12	1.38	–
Yang et al., 2014	JiangSu	36.48	18.58	11.67	16.85	5.66	0.84	–	0.77	0.46
Zhao et al., 2023	Tangshan	60.12	12.56	8.02	5.10	3.11	1.30	–	–	–
Duarte et al., 2022	Brazil	54.10	44.80	0.43	0.06	0.03	0.05	–	0.43	–
Yin et al., 2019	Shanxi	36.94	16.96	10.38	11.04	7.94	0.37	0.22	1.19	5.97
Chen et al., 2023a, 2023b Yu et al., 2024	Maanshan	61.63	11.09	16.22	6.35	2.86	0.32	–	0.29	0.17

the IOTS content was 25%–50% (Tang et al., 2019a, 2019b). Recently, Jayasimha et al., (2022) explored the mechanical properties of IOTS concrete with different mix ratios, and revealed that the compressive strength of concrete with less than 40% IOTS at all ages was superior to that of control concrete. Test results of 56d showed that the compressive strength of concrete containing 20%, 30%, 40% and 50% IOTS increased respectively by 4.0%, 6.3%, 6.86% and 1.0% compared with control concrete. Additionally, Cao (2021) found that the maximum compressive strength of IOTS concrete was obtained at 70% content when the IOTS particle size was less than 4.75 mm, as shown in Fig. 4a.

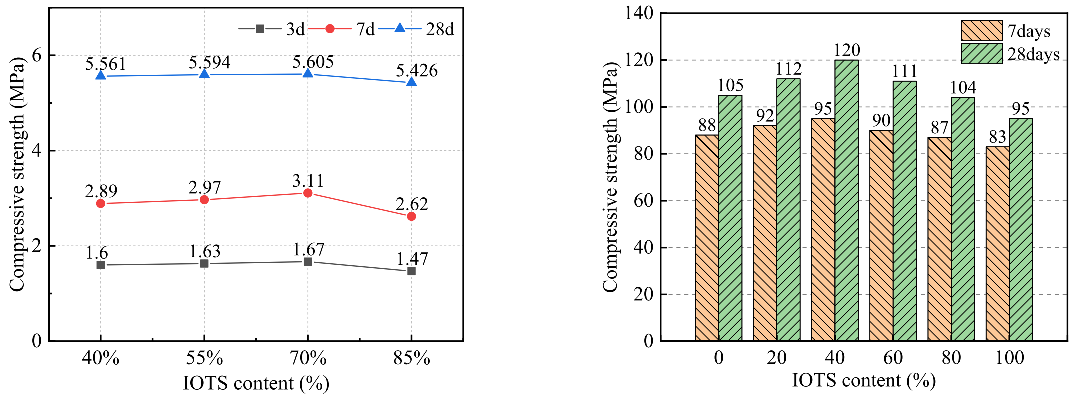
Clearly, there is inconsistency regarding the optimal mix ratio for IOTS concrete. However, it is worth noting that after reaching the optimum mix, continuing to increase the IOTS content lowers the workability and mechanical properties. Scholars have suggested different optimum levels of IOTS (ranging from 20 to 70%) for the production of concrete (Chen et al., 2023a, 2023b; Shetty et al., 2014; Zhang et al., 2020; Zhu et al., 2015), as shown in Fig. 4b. Differences in optimal mix ratio might be related to mineralogical composition of geological exploration region that produced IOTS.

3.2 Workability

Obviously, workability is an essential prerequisite for obtaining favorable mechanical properties and durability. Generally, slump value is employed to evaluate quantitatively the workablitily of IOTS concrete. Incorporation of IOTS into concrete enhances the water demand and decreases the flowability due to rough surface of IOTS and high specific surface area (Zhao et al., 2014). Comparatively, slump value of IOTS concrete is smaller than that of NS concrete, and it also exhibits a tendency of decreasing with the increase of the amount of IOTS (Deng et al., 2010; Ugama et al., 2014; Shettima et al., 2016; Xu et al., 2019; Liu et al., 2022; Ling et al., 2023), as shown in Fig. 5. This is mainly because, compared with the ordinary smooth surface of the river sand, IOTS surface is rough and angular, friction between particles is relatively large, which is not conducive to improving free flow of fresh concrete. Additionally, the specific surface area of IOTS is greater than that of NS, and more cementitious materials are required to maintain the slump of fresh concrete.

It is noteworthy that a small number of investigations have shown inconsistent influence laws. The test results of (Jayasimha et al., 2022) showed that the slump of concrete containing 50% IOTS was 13.3% higher than that of control concrete. This phenomenon might be caused by the reasons as (1) the inclusion of a small amount of IOTS might adjust particle gradation of fine aggregate and improve the flow performance of newly mixed concrete; (2) IOTS contained some ultra-fine components, which might act as the cementing ingredient and improve the fluidity.

Furthermore, some scholars have concluded different influence rules and found that slump value was related to the content of IOTS concrete. The slump of IOTS concrete increased and then decreased as IOTS content increased (Huang et al., 2019; Jiang et al., 2019; Tang et al., 2019a, 2019b). The concrete slump was maximized when the IOTS content was increased to 25%. Meanwhile, the effect of IOTS content on the slump of IOTS-steel slag concrete was studied, and it was found that the



(a) effect of IOTS content (Cao et al., 2021) (b) optimum IOTS content 40% (Zhang et al., 2020)

Fig. 4 Influence of IOTS content on compressive strength of samples at different ages

slump of the concrete increased and then decreased with the increase of IOTS content (Cao, 2021), as shown in Fig. 6, which might be because the content of concrete slurry gradually increased, the slurry could play a lubricating role, reduce the friction resistance of coarse aggregate and enhance concrete fluidity (Tang et al., 2019a, 2019b). However, as IOTS content continued to increase, the surface of IOTS became rough and angular, which made the concrete more prone to segregation and water seepage, affecting the cohesion and water retention of concrete**.** Similarly, the study of Jiang et al (2019) showed that when the IOTS content was 30%, the slump could reach the maximum of 195 mm, while as IOTS content increased to 60%, the slump decreased to 80 mm.

3.3 Mechanical Properties of IOTS Concrete

The mechanical properties of IOTS concrete, including compressive, spiting tensile, flexural strength and elastic modulus, are summarized in this section.

3.3.1 Compressive Strength

Numerous existing researches had shown that the compressive strength of IOTS concrete was related to content and fineness of IOTS. When the fineness of IOTS was similar to that of NS, the difference in compressive strength between IOTS concrete and NS concrete was marginal, whereas when the fineness of IOTS was smaller than that of NS, the compressive strength of IOTS concrete increased and then decreased as IOTS content increased (Shettima et al., 2016; Tang et al., 2019a, 2019b; Kumar et al., 2019). The research results of Sunil et al., (2015) revealed that the concrete with 30%–40% IOTS content was increased by 9.19%–8.91% compared with control group, as shown in Fig. 7a. Similarly, Li et al., (2016) reported that concrete with 25%–50% IOTS content increased by 2.1%–3.5% compared with control group, while compressive strength of concrete with 100% IOTS content decreased by 1.63%, as shown in Fig. 7(b). Recently, it was found that 28 days compressive strength of IOTS concrete was larger than that of control group when IOTS content was not exceeded 40%. The compressive strength of concrete with IOTS content of 20%

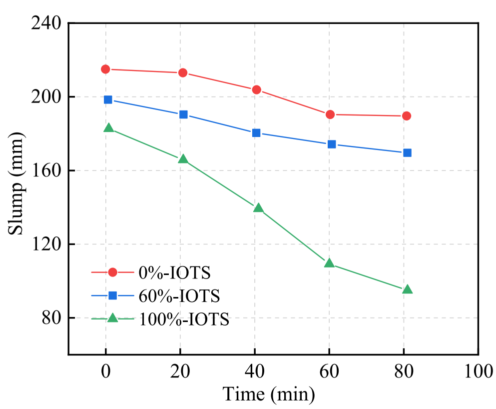


Fig. 5 Variation of sample slump with time at different IOTS contents (Deng et al., 2010)

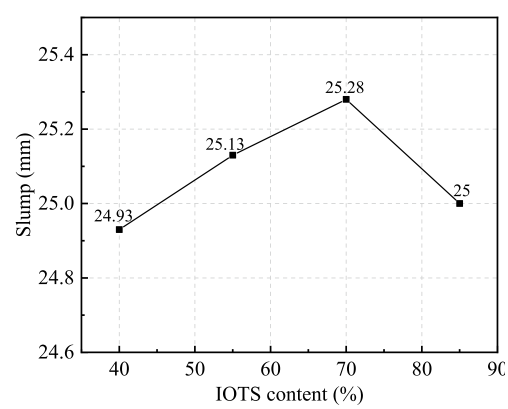


Fig. 6 Effect of IOTS content on slump (Cao, 2021)

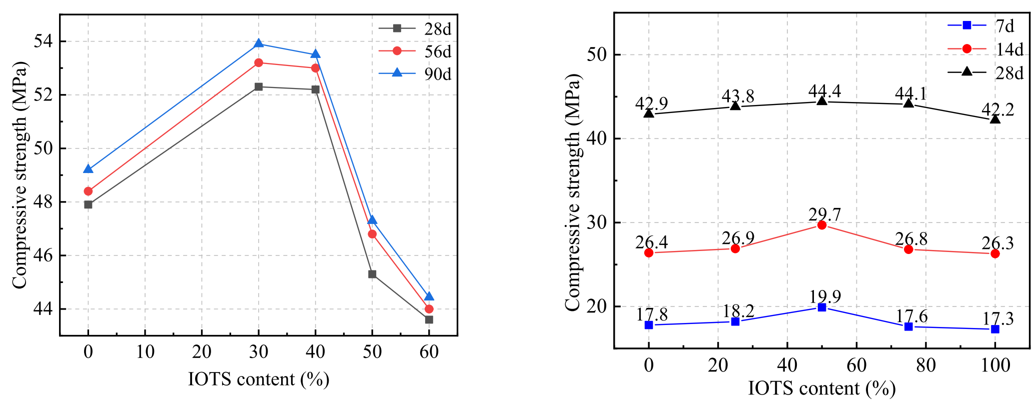


Fig. 7 Effect of content on compressive strength of samples at different ages

and 40% was 3.56% and 5.34% higher than that of control group, respectively. When IOTS content exceeded 40%, the concrete strength was smaller than that of control group, and compressive strength of concrete with 60%, 80% and 100% IOTS content was 6.7%, 9.16% and 14.47% lower than that of control group, respectively (Liu et al., 2022). Apparently, currently there is inconsistency regarding the compressive strength for IOTS concrete. The reason was that the origin and fineness of IOTS were different, fine-grained IOTS could favorably optimize the pore structure (Uchechukwu et al., 2014; Liu et al., 2023), effectively filled internal void of concrete, and improve concrete compactness. Meanwhile, the rough surface and many angles of IOTS could improve the adhesion with cement paste. However, when the IOTS content was high, due to the poor grading degree, the defects gradually became obvious and porosity and micro-cracks increased (Xu et al., 2020, 2021). Additionally, the specific surface area of IOTS was large, and the amount of cement slurry attached to IOTS per unit area decreased, weakening bonding force between aggregates.

3.3.2 Splitting Tensile Strength

Tensile strength is a key indicator for measuring the crack resistance of concrete and an important parameter for indirectly determining bond strength between concrete members. In view of discreteness of test data of axial tensile strength of concrete, the splitting tensile strength test method is usually adopted to measure concrete tensile strength, which provides easy operation and high precision.

A series of research results showed that the influence of IOTS content on tensile strength was consistent with that of the above compressive strength, exhibiting a trend of increasing and then decreasing (Li et al., 2021; Arbili et al., 2022; Tao et al., 2023). It was indicated that the splitting tensile strength of concrete with 20%, 40%, 60% and 80% IOTS content increased by 8.72%, 18.16%, 9.56% and 5.19% compared with ordinary control concrete, respectively (Liu et al., 2022). The reduced splitting tensile strength of IOTS concrete was attributed to the fact that excessive IOTS content would lead to inferior adhesion between aggregates and weak inter-facial transition zones. Similar conclusions were drawn by Tanvir (2021) and Wu et al., (2012), further confirming that the concrete with 40% IOTS content exhibited the best splitting tensile strength, as shown in Fig. 8. Differently, Shettima et al., (2016) and Kumar et al., (2019) suggested that the optimum IOTS content were 15% and 25%, respectively as shown in Fig. 9.

To explore the correlation between splitting tensile strength f_{st} and compressive strength f_{cu}, the form of the formula for the correlation between f_{st} and f_{cu} suggested in ACI 318 (2019), ACI 363R (1992) and EC4 (2004) specifications was referred, as shown in Eqs. (1–3), and the correlation between the f_{st} and f_{cu} of IOTS concrete

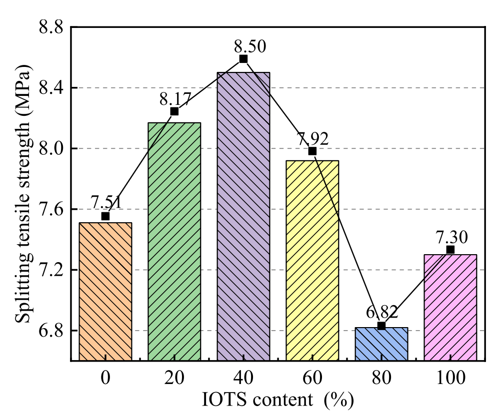


Fig. 8 Results of 28 day splitting compressive strength of samples with different IOTS contents (Tanvir et al., 2021)

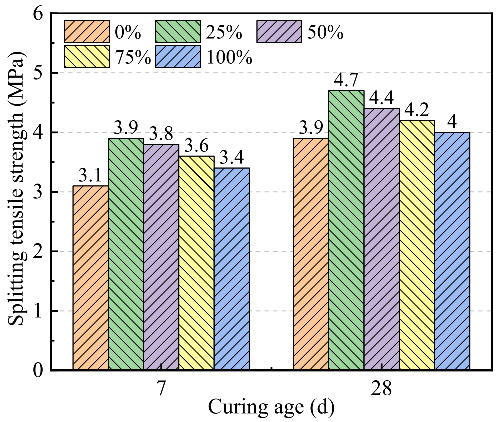


Fig. 9 Influence of IOTS content on splitting tensile strength of samples at different ages (Shettima et al., 2016)

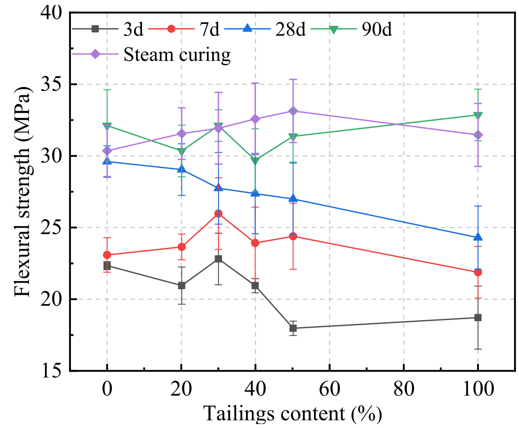


Fig. 10 Flexural strength of IOTS concrete sample at different ages (Zhao et al., 2014)

was fitted by Liu et al., (2022) based on a large number of test data, as shown in Eq. (4). Similar work was also carried out by Zhao et al., (2021a, 2021b), on the basis of the Eq. (5) of f_{st} and f_{cu} of ordinary concrete suggested by Chinese code GB/T50010 (2010) and a large number of collected test data, the correlation relationship was established in Eq. (6).

$$f_{st} = 0.53 f_{cu}^{0.5} \tag{1}$$

$$f_{st} = 0.59 f_{cu}^{0.5} \tag{2}$$

$$f_{st} = 0.3 f_{cu}^{0.67} \tag{3}$$

$$f_{st} = 0.125 f_{cu}^{0.91} \tag{4}$$

$$f_{st} = 0.19 f_{cu}^{0.75} \tag{5}$$

$$f_{st} = 0.19 f_{cu}^{0.73} \tag{6}$$

3.3.3 Flexural Strength

Similarly, flexural strength is also an important indicator of material properties. In contrast, flexural strength is more sensitive to features in micro-structure than compressive strength (Toutanji and Bayasi, 1999; Cao et al., 2000). The research results of Zhao et al., (2014) showed that under standard curing conditions, the inclusion of IOTS exerted little effect on concrete early flexural strength, and flexural strength of concrete with 20%, 30% and 100% IOTS content at 3d and 7d were even greater than that of control group. However, when IOTS content ranged from 20 to 50%, the flexural strength of sample at 28d approximately decreased by 20%, and decreased by 29% for the concrete with 100% IOTS content, as shown in Fig. 10. Meanwhile, it was found that the flexural strength of concrete with low IOTS content (less than 40%) increased slightly as IOTS content increased, while it decreased as IOTS content increased when IOTS content exceeded 40% (Chen et al., 2017). A similar conclusion was drawn by Li (2017) that as the increase of IOTS content, the flexural strength increased and then decreased. This influence law coincides with the variation rule of IOTS content on the compressive and flexural strength. The reason for this variation is also similar to the mentioned above explanations.

In addition, some scholars have attempted to establish the correlation between flexural strength f_f and compressive strength f_{cu} of IOTS concrete. On the basis of Eq. (7) of f_f and f_{cu} of ordinary concrete suggested by ACI 318 (2019) and ACI 363R (1992) codes, the correlation between f_f and f_{cu} of IOTS concrete was fitted by Zhao et al., (2012) based on a large amount of collected test data, as shown in Eq. (8).

$$f_f = 0.54 f_{cu}^{0.5} \tag{7}$$

$$f_f = 0.42 f_{cu}^{0.73} \tag{8}$$

3.3.4 Elastic Modulus

Comparatively, relatively few investigations have been conducted on elastic modulus of IOTS concrete, and the limited studies available had derived inconsistent results. The 28 days elastic modulus of concrete with 20%–100% IOTS contents was studied, indicating that elastic modulus of IOTS concrete increased as IOTS content increased, and it increased by 45.37%–65.74% compared

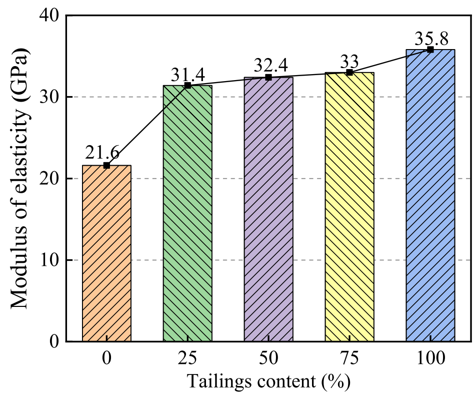


Fig. 11 28-day elastic modulus of samples with different IOTS contents (Shettima et al., 2016)

with control group, as shown in Fig. 11 (Shettima et al., 2016). This may be due to the following reasons (1) the addition of IOTS improves the particle gradation between aggregates; (2) the rough surface and angular structure of IOTS enhance the bonding effect between cement and aggregates; (3) the $Ca(OH)_2$ generated by hydration of cement reacts with IOTS in secondary hydration, continuously fills the internal pores of the samples, and the compactness is constantly improved, which leads to the enhancement of deformation resistance.

Differently, the opposite conclusion was reached, finding that elastic modulus of concrete with 20%–60% IOTS content decreased by 0.53%–3.74%, as shown in Fig. 12 (Wang et al., 2018). Similar conclusion was also drawn by Tao et al., (2023). This was mainly due to the high mud content in IOTS and the irregular shape of its particles, which could easily lead to the separation of aggregate from mud and segregation when the mud content was excessive, thus reducing the strength of IOTS concrete and leading to the continuous reduction of elastic modulus.

Moreover, the results of Chen et al., (2017) revealed that the elastic modulus of IOTS concrete with 40% IOTS content increased by 0.77% compared with control group, while elastic modulus of concrete with 50%–70% IOTS content decreased by 1.93%–2.57%, as shown in Fig. 13. This was mainly because the irregular angular structure on the surface of IOTS led to more pores inside the concrete structure, preventing the reaction between cement and water, thus reducing the actual water-binder ratio. The increase of effective gels system at the aggregate interface and the strengthening of the chemical binder force of cement made the bond between the aggregates inside the concrete structure dense, reducing the deformation rate of the materials, and thus increasing elastic modulus. However, the surface of IOTS had uneven edge angle, which was easy to be damaged in the process of stress, resulting in the reduction of elastic modulus.

In contrast, there are relatively few studies on elastic modulus and the conclusions are inconclusive. In view of the inconsistency of the current research results and the limited number of data samples, the subsequent research on elastic modulus of IOTS concrete needs to be further conducted.

3.4 Drying Shrinkage

Due to evaporation of free water, hardened concrete inevitably produces drying shrinkage, and several microcracks will occur in concrete when the shrinkage stress is larger than concrete tensile strength (Deysel et al., 2023). With the drying shrinkage gradually increasing,

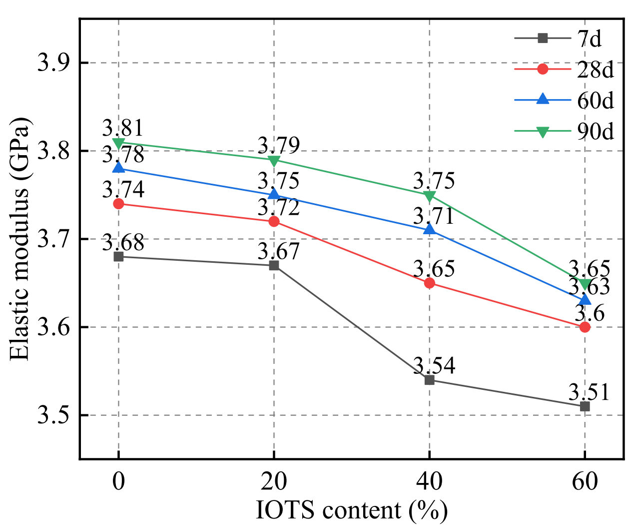


Fig. 12 Effect of IOTS content on elastic modulus of samples at different ages (Wang et al., 2018)

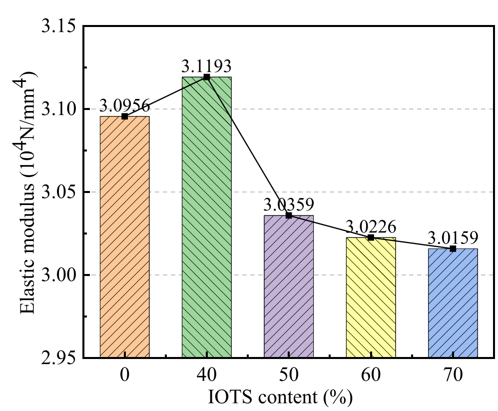


Fig. 13 Elastic modulus of samples with different IOTS content (Chen et al., 2017)

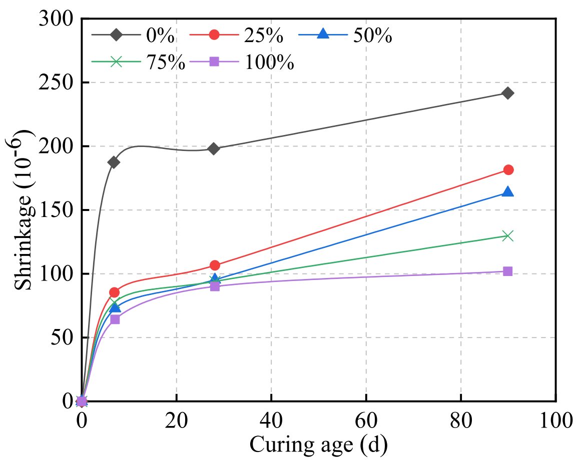


Fig. 14 Effect of IOTS content on shrinkage properties of samples at different ages (Shettima et al., 2016)

cracks gradually become distinct. Drying shrinkage is also a critical indicator of concrete long-term behavior. The research results of Shettima et al., (2016) reported that drying shrinkage of concrete with IOTS content of 25%, 50%, 75% and 100% at 90 days were 24%, 43%, 46% and 58% lower than control group concrete, as shown in Fig. 14. A similar conclusion was also drawn for the concrete made of IOTS and manufactured sand, the drying shrinkage of IOTS concrete with C30, C50 and C60 grades was examined, and it was found that the drying shrinkage was lower than control group concrete (Jia et al., 2013; Feng et al., 2011). Additionally, Zhang et al., (2013) found that drying shrinkage of mixed sand concrete was smaller than that of NS concrete and decreased as the IOTS content increased.

Clearly, the conclusion of existing studies (Feng et al., 2011; Jia et al., 2013; Shettima et al., 2016; Wang et al., 2022; Deysel et al., 2023) was basically the same, the drying shrinkage of IOTS concrete decreased as IOTS content increased. This could be attributed that the following reasons (1) filling effect of fine IOTS on pore structure; (2) the porosity of IOTS concrete would absorb more moisture during the concrete drying stage and release moisture slowly; and (3) the microstructure built on the multi-angular surface of IOTS were relatively stable.

3.5 Durability of IOTS Concrete

Durability refers to the capacity of concrete to withstand the action of environmental media, to maintain its favorable performance and appearance integrity chronically, and to sustain the safety and normal use of the structures. The durability of concrete affects the service life of the structures. This section focuses on the research progress of durability of IOTS concrete from the aspects of permeability, frost resistance and carbonation resistance.

3.5.1 Permeability Resistance

Rapid chloride penetration and water penetration tests are employed to assess the permeability of IOTS concrete. Permeability is closely correlated to IOTS content in concrete. The research result of Feng et al., (2017) and Wang et al., (2023) showed that the relative permeability coefficient of IOTS concrete decreased and then increased as IOTS content increased, and the recommended optimal IOTS content was 25%. However, a different conclusion showed that when IOTS content was less than 20%, the permeability resistance of IOTS concrete increased as IOTS content increased, while decreased as IOTS content increased when IOTS content was more than 20%, and the impermeability of IOTS concrete was 1.78×10^{-5}–5.96×10^{-6} cm/h (Wang et al., 2020). Meanwhile, the permeability resistance of concrete with different IOTS contents (i.e., 0%, 20%, 40%, 60%, 80% and 100%) was analyzed, finding that the impermeability increased as IOTS content increased, as shown in Fig. 15 (Zhang et al., 2020). Additionally, an experimental study on permeability resistance of IOTS and fly ash concrete with large dosage was also conducted, confirming that under the same water-cement ratio, the compressive and tensile strength of IOTS concrete were lower than that of fly ash concrete, while the chloride ion permeability resistance was larger than that of fly ash concrete (Han et al., 2017, 2020).

Obviously, there are some deviations in the conclusions drawn by the scholars, which might be related to the different sources and mineral compositions of the IOTS used in the experiments. However, the reason that the incorporation of IOTS could improve the impermeability of concrete might be attributed to the following reasons

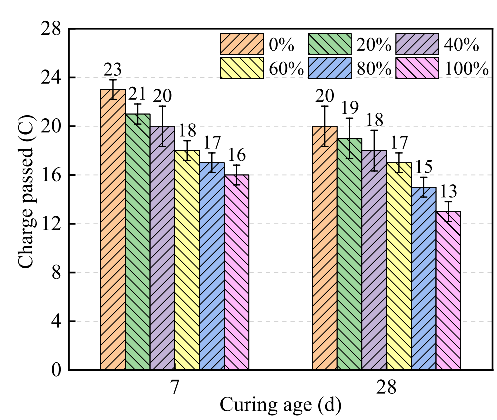


Fig. 15 Permeability test under different IOTS contents (Zhang et al., 2020)

(1) fine IOTS could fill the voids, optimize the pore structures and decrease porosity; (2) some ultra IOTS particles consumed $Ca(OH)_2$ and produced more C-S–H, thus resulting in dense and uniform structures (Han et al., 2017; Shettima et al., 2016).

3.5.2 Frost Resistance

The frost resistance is the capacity of a material to resist multiple freeze–thaw cycles in the state of water without damage and significant reduction in strength, which is a critical indicator for assessing concrete durability in cold conditions (Cheng et al., 2020; Wang et al., 2022).

The result of Zhang et al., (2014) revealed that the addition of IOTS had little effect on the frost resistance of the samples compared with the NS, the strength loss and weight loss of concrete with IOTS content of 20%–60% were less than 22% and 5% respectively after 200 freeze–thaw cycles. The freeze–thaw cycle tests of IOTS concrete respectively was carried out, and it was found that with the increase of IOTS content, the freeze-resistance of the samples increased and then decreased, and the frost resistance of concrete with 30% IOTS content was comparable to that of NS concrete, as shown in Fig. 16 (Cheng et al., 2020; Feng et al., 2017). The freeze–thaw cycle tests on IOTS concrete exposed to different proportions of NaCl solution were also performed, revealing that the freeze–thaw cycle increased the diffusion rate of Cl^- to the concrete interior, and the compressive strength decreased as the number of cycles increased (Zhang et al., 2018).

Obviously, the previous studies (Cheng et al., 2020; Wang et al., 2022, 2023; Zhang et al., 2014, 2018) had demonstrated that there was little difference in the frost resistance between IOTS and NS at appropriate content, and the frost resistance of samples increased and then decreased with the addition of IOTS. This might be due to the following reasons (1) IOTS had high water absorption, and with the freeze–thaw cycle, the free water in the internal pores of concrete kept freezing and expanding; (2) the addition of IOTS optimized the particle size gradation of aggregates, while IOTS was inactive substances, with the progress of freeze–thaw cycle, the hydration reaction of IOTS continuously occurred, and microcracks continuously occurred on the sample surface; (3) excessive addition of IOTS destroyed the integrity of the concrete structure, resulting in the increase of harmful pores.

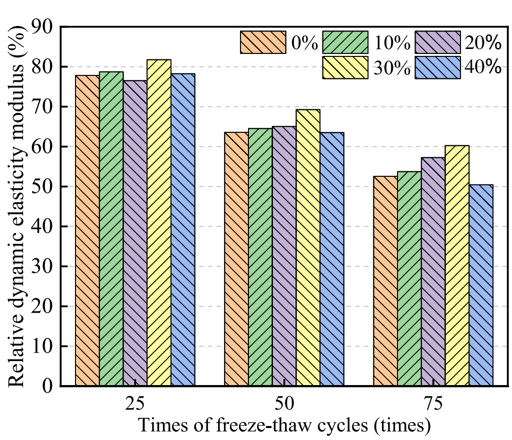


Fig. 16 Effect of IOTS content on relative dynamic elastic modulus of samples under different freeze–thaw conditions cycles (Cheng et al., 2020)

Apparently, from the available studies, it could be suggested that subsequent attention should be focused on the effect of more relevant influencing factors on the frost resistance of IOTS concrete, in-depth research on the anti-freezing mechanism of IOTS concrete, and relevant prediction models for the anti-freezing performance of IOTS concrete should be proposed.

3.5.3 Carbonation Resistance

Carbonation is a relatively slow chemical process in which CO_2 in the atmosphere reacts with $Ca(OH)_2$ in concrete to form $CaCO_3$. Concrete carbonation exerts little effect on strength, while the effect on steel in concrete should not be ignored. Currently, the influence law of IOTS content on carbonation resistance was inconsistent. Shettima et al., (2016) reported that the carbonation depth reduced as IOTS content increased, and compared with NS concrete, carbonation depth of concrete with 100% IOTS content decreased by 51.98%. Subsequently, it was also reported that the incorporation of 20% IOTS content was conducive to reducing the carbonation depth, and the low water-binder ratio was benefit to improve the carbonation resistance (Song et al., 2019). Meanwhile, the impact of IOTS content and water-binder ratio on carbonation resistance of concrete was examined, revealing that the carbonation resistance decreased as IOTS content increased, and the optimal water-binder ratio of IOTS concrete was 0.4, as shown in Fig. 17 (Sun and Liu 2020). Obviously, most research results demonstrated that the introduction of IOTS contributed to the reduction of carbonation depth. This might be attributed to the incorporation of IOTS was conducive to compacting void and optimizing pore structure, thus avoiding or delaying the entry of CO_2.

Differently, some scholars drew an opposite conclusion that carbonation depth of IOTS concrete increased as IOTS content increased. The carbonation resistance of concrete with different contents of IOTS (i.e., 10%, 20%, 30%, and 40%) was investigated, demonstrating that carbonation resistance decreased as IOTS content

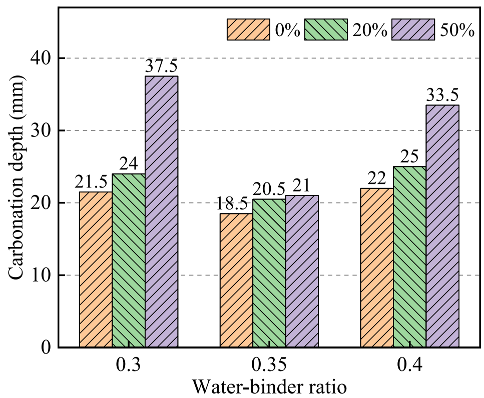


Fig. 17 Effect of IOTS content on carbonation depth of samples (Sun et al., 2020)

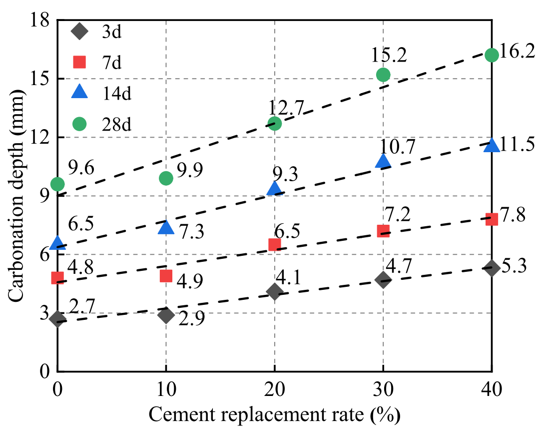


Fig. 18 Effect of IOTS content on carbonation depth of sample (Cheng et al., 2020)

increased, as shown in Fig. 18 (Cheng et al., 2020). The main reason for the decrease in carbonation depth might be came from that the addition of fine IOTS made the cement clinker content relatively reduced, the production of $Ca(OH)_2$ decreased, resulting in the reduction of alkalinity. Additionally, the pozzolanic reaction of fine IOTS consumed $Ca(OH)_2$, which further reduced concrete alkalinity, leading to a decline in carbonation resistance.

4 Mechanical Behaviors of IOTS Concrete Members

As mentioned above, the application of IOTS concrete in engineering structural components is an effective way to realize the recycling and large-scale utilization of solid waste. Currently, numerous researches have been conducted on material properties of IOTS concrete, and fruitful achievements have been made. Comparatively, relatively few studies have focused on the component level of IOTS concrete, and there is a lack of systematic research on IOTS concrete members.

In terms of experimental research, experimental studies on flexural behaviors of IOTS concrete members were conducted, demonstrating that IOTS content was closely correlated to flexural behaviors of beam and slab specimens, and the crack width was positively correlated with IOTS content (Guan et al., 2016, 2017). Considering the effects of factors, such as concrete strength grade and diameter of longitudinal reinforcement, the various mechanical properties of IOTS concrete beams and ordinary concrete beams were comparatively analyzed and it was indicated that there was little difference between the mechanical properties of the two types of beams, which largely confirmed the feasibility of using IOTS instead of NS for concrete (Bhargav 2021; Wang et al., 2015). In addition, the flexural behaviors of RC beams with different IOTS contents were investigated and it was found that the replacement of NS by IOTS had marginal effect on flexural strength, whereas exerted a greater impact on the deflection of beams. When the replacement rate of IOTS was 40%, the deflection of IOTS concrete beams was the maximum (Prema et al., 2014). Similarly, the influences of several parameters, such as IOTS replacement rate, reinforcement ratio, slab thickness, on the mechanical behaviors of IOTS concrete beams and slabs were analyzed, demonstrating that when IOTS content reached 70%, the shear behaviors of IOTS concrete beams and NS concrete beams were significantly different, while the flexural behaviors of IOTS concrete slabs were little different from those of NS concrete slabs (Chen 2015; Ma et al., 2024). The flexural behaviors of RC beams prepared by partially replacing fine aggregate using IOTS with a small amount of sisal fibers was examined and it was revealed that when IOTS content was 25% and sisal fiber was 1%, the flexural capacity of IOTS

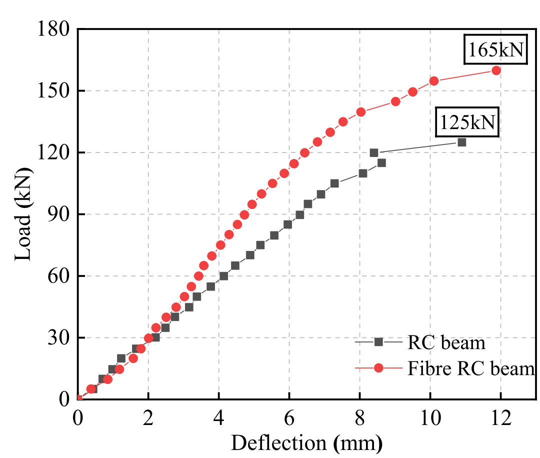


Fig. 19 Comparison of load–deflection curves of beams (Bhargav et al., 2021)

concrete beam was 28% higher than that of NS beam (Bhargav et al., 2021), as shown in Fig. 19. Additionally, an experimental study on axial compression behavior of IOTS concrete short columns with different strength levels was conducted, finding that the axial capacity of IOTS concrete short columns was similar to that of NS concrete short columns, considerably indicating that IOTS could be used in axial compression members instead of NS (Li and Kang 2018). Relatively few studies have been conducted on the performance of IOTS concrete compression members, and their application in structural engineering requires further research.

In terms of numerical simulation, the impacts of IOTS content and shear span ratio on mechanical behaviors of IOTS concrete beams were simulated and the analysis results indicated that the incorporation of IOTS reduced the shear behavior of beams, and the decrease in shear span ratio improved the capacity of IOTS beams (Hu et al., 2015; Cao et al., 2019). A similar numerical simulation study was carried out for the IOTS concrete slabs, the influences of slab thickness and reinforcement ratio on the flexural behaviors of IOTS concrete slabs were analyzed and it was found that similar to normal concrete slabs, increasing reinforcement ratio or slab thickness would improve load capacity and flexural stiffness of IOTS concrete slabs (Zhu, 2015). In addition, a simulation study on axial compression behavior of IOTS concrete columns was conducted, and the influence of stirrup characteristic value and concrete strength grade on axial compression behavior was examined (Zhang et al., 2016). Simulation analysis illustrated that increasing concrete strength grade improved column stiffness, and the peak stress and peak strain of IOTS concrete were positively correlated with the stirrup characteristic value. Currently, numerical simulation studies on IOTS concrete members are very limited and the analysis depth needs to be further deepened. The relevant numerical simulation research can be further carried out in the future.

In terms of theoretical research, scholars have also carried out relevant research work. To explore the applicability of the calculation formulas of cracks and stiffness of ordinary RC beams in existing Chinese code GB 50010 (2010) to IOTS beams, the flexural behaviors of IOTS concrete beams and ordinary RC beams were compared and analyzed, demonstrating that the calculation formula of stiffness was suitable for IOTS concrete beams while the compatibility of crack width formula was general. On the basis of the existing specification, the formula for predicting crack width of IOTS concrete was proposed, and the prediction formula of average crack width and maximum crack width prediction formula are shown in Eq. (9) and Eq. (10) (Zhang et al., 2015).

$$l_{\mathrm{m}} = 2.2c + 0.0781d/\rho_{\mathrm{te}} \tag{9}$$

$$w_{\mathrm{m}} = 1.905\frac{\sigma_{\mathrm{s}}}{E_{\mathrm{s}}}l_{\mathrm{m}} \tag{10}$$

where, l_{m} is the average crack width, c is the thickness of protective layer, d represents the longitudinal reinforcement diameter and ρ_{te} denotes the longitudinal tensile steel reinforcement ratio calculated by section area of effective tensile concrete, w_{m} is the maximum crack width, σ_{s} is the equivalent stress of longitudinal tensile reinforcement of concrete member calculated according to standard combination and E_{s} is the elastic modulus of steel reinforcement.

Considering the impact of shear span ratio, reinforcement ratio and concrete strength grade, the shear behavior of IOTS concrete beams and ordinary RC beams was compared and analyzed, a suitable formula for calculating shear capacity of IOTS concrete beams based on shear capacity formula of ordinary RC beams was proposed (Ma et al., 2021; Wang, 2019), as shown in Eq. (11).

$$V_s = \frac{\alpha}{\beta + \lambda}f_t b h_0 + f_{yv}\frac{A_{sv}}{s}h_0 \tag{11}$$

where, V_{s} is the shear capacity of IOTS concrete, α and β are the correction coefficients for IOTS concrete compared to ordinary concrete, respectively, λ takes 2.0 and 2.5, f_{t} is the tensile strength of concrete, b is the beam section width, h_0 is the effective height of beam section, f_{yv} is the tensile strength of stirrups, A_{sv} is the stirrup area and s is the stirrup spacing.

In addition, the impact of axial compression ratio, hoop characteristic value and concrete strength grade on seismic behavior of IOTS concrete columns was also examined, and the prediction formula of the flexural bearing capacity of IOTS concrete columns was derived based on the existing formula in Chinese code GB50010 (2010) and a large number of test results (Li et al., 2018), as shown in Eq. (12) and Eq. (13).

$$f_{\mathrm{c}} = K0.67f_{\mathrm{cu}} \tag{12}$$

$$K = 1 + \frac{\rho_{\mathrm{v}}f_{\mathrm{ys}}}{0.79f_{\mathrm{cu}}}(K \leq 1.2) \tag{13}$$

where, $f_{\mathrm{c}}$is the compressive strength of concrete under stirrup confinement, f_{cu} is the compressive strength of IOTS concrete, f_{ys} is the yield strength of stirrups, ρ_{v} is the volume reinforcement ratio of the stirrup and K is the increasing coefficient of compressive strength of concrete under stirrup confinement.

To sum up, the existing studies of IOTS concrete members mainly focuses on flexural members, and the limited research results demonstrate that the failure mode of concrete flexural members with IOTS is similar to those of ordinary RC flexural members. The mechanical behaviors of the IOTS concrete members with appropriate IOTS content are equal to or even exceed those of ordinary RC members. It is feasible to rationalize the application of IOTS concrete to engineering structural members. However, it's worth noting that most of IOTS currently used in concrete members are medium sands, and few reports are available on the application of fine and ultra-fine IOTS. Future research will be directed towards further consideration of the properties of fine and ultra-fine IOTS concrete and the behavior of its concrete members, as well as the development of new and effective ways to utilize IOTS resources.

5 Conclusion and Future Needs

A summary review of findings and investigations on the basic material properties of the IOTS concrete is presented, as well as the mechanical behaviors of IOTS concrete members. Conclusions can be summarized:

(1) The basic material characteristics of IOTS, such as physical properties and mineral composites, and the similarities and differences between IOTS and NS were compared and analyzed. The apparent density, porosity and water absorption of IOTS were generally greater than those of NS. The mineral composite of IOTS mainly included SiO_2, Fe_2O_3 and Al_2O_3.
(2) Different conclusions were reached on the workability of IOTS concrete, while it was worth affirming that the workability of concrete was related to the IOTS content. The rough, angular surface and large specific surface area of IOTS resulted in the decrease of slump of IOTS concrete. Conversely, the fine or ultra-fine IOTS could adjust the particle gradation of fine aggregate, act as the cementing ingredient and improve flow properties.
(3) The mechanical properties of IOTS concrete were systematically summarized from the aspects of compressive, splitting tensile, flexural strengths and elastic modulus. Except for elastic modulus, the other properties generally showed the similar rules, which increased and then decreased as IOTS content increased. Additionally, the drying shrinkage of IOTS concrete decreased with increasing IOTS content. This was mainly attributed to the favorable filling effect of fine IOTS and the stable microstructure formed on multi-angular surface.
(4) The research progress of durability of IOTS concrete, including the permeability, frost and carbonation resistances, was summarized in detail. The appropriate incorporation of IOTS could improve the impermeability, frost resistance and carbonation resistance. The inconsistent effect of IOTS content on concrete durability was mainly due to the different mineralogical compositions of the geological exploration areas where IOTS was generated.
(5) The mechanical behaviors of IOTS concrete members were summarized in terms of experimental research, theoretical analysis and numerical simulation. The limited research mainly focused on the IOTS concrete flexural members. Concrete members with appropriate IOTS content behaved equal or even higher mechanical behaviors than those of ordinary RC members, which considerably confirmed the feasibility of using IOTS instead of NS for concrete in engineering.

From the current research, the study on IOTS concrete (especially at the component level) is still in its infancy and relatively limited work has been conducted on IOTS concrete and members. Further research can be conducted as follows:

(1) Searching for suitable and effective ways to utilize fine or ultra-fine IOTS, as well as seeking appropriate solid waste materials to cooperate with the IOTS to improve the workability, mechanical properties and durability of concrete are future research directions of interest.
(2) Most of the existing researches are mainly focused on the material level, while comparatively few studies have been conducted at the component level. Further research on the mechanical behaviors of IOTS concrete members can be conducted in the future.
(3) Exploring the durability of IOTS concrete and its members, and revealing the degradation mechanism are also essential research topics that needs urgent attention in the future.

Acknowledgements
The paper has been completed thanks to all those involved, who have provided valuable wealth of knowledge and experience.

Author contributions
Yuan Fang: Methodology, Validation, Formal analysis, Data curation, Writing—original draft, Funding acquisition. Lijie Qiao: Formal analysis, Data curation, Supervision. Tao Hu: Investigation, Data curation. Lu Zhang: Investigation, Supervision. Hongming Long: Investigation, Data curation, Writing—review & editing. Feng Yu: Investigation, Funding acquisition, Writing—review & editing. Zhixin Yang: Conceptualization, Investigation, Writing—review & editing.

Funding
This study was sponsored by the Key Research and Development Project of Anhui Province (No.2022i01020005), Major Science and Technology Project of Anhui Province (No. 202203a07020005), The University Outstanding Research

and Innovation Team Program of Anhui Province (No. 2023AH010017), The University Synergy Innovation Program of Anhui Province (No. GXXT-2023–061, GXXT-2022–074), and Key Laboratory of Metallurgical Emission Reduction & Resources Recycling (Anhui University of Technology), Ministry of Education (No. JKF22-08).

Data Availability
Data availability is not applicable to this article as no new data were created or analyzed in this study.

Declarations

Ethics Approval and Consent to Participate
Not applicable.

Consent for Publication
The author agrees about submission to the journal.

Competing interests
We declare that we have no compete of interests.

Received: 3 October 2024 Accepted: 1 March 2025
Published online: 03 June 2025

References
ACI 363R. (1992) Report on High-Strength Concrete. American Concrete Institute, Farmington Hills, MI.
ACI 318. (2019) Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Farmington Hills, MI.
Arbili, M. M., Alqurashi, M., Majdi, A., Ahmad, J., & Deifalla, A. F. (2022). Concrete made with iron ore tailings as a fine aggregate, a step towards sustainable concrete. *Mater., 15*(18), 6236. https://doi.org/10.3390/MA15186236
ASTM C33/C33M. Standard specification for concrete aggregates. ASTM International, West Conshohocken, PA, 2018.
Bhargav, M., Khadar, S. A. R. S. A. (2021) Characterization of fibre R.C beam made with partial replacement of sand with iron ore. Mater Today: Proc. 45 (P7): 6590–6595. https://doi.org/10.1016/J.MATPR.2020.11.769
Bian, L. B. (2008) The research of high-performance concrete with superfine tail mineral sand. Ready-Mixed Concr. 11–14.
Cao, C., Sun, W., & Qin, H. G. (2000). The analysis on strength and fly ash effect of roller-compacted concrete with high volume fly ash. *Cement and Concrete Research, 30*(01), 71–75. https://doi.org/10.1016/S0008-8846(99)00203-3
Cao, C. H., Weng, W. S., Ma, C. Y., Sun, X. H., Guo, H. L., Pan, H. B., & Yang, N. (2019). Numerical simulation of shear behavior of pumice concrete beam with iron tailings sand. *Journal of Hebei Institute of Architecture and Civil Engineering., 38*(02), 6–13.
Cao, Y. (2021). Preparation and performance study of composite excited iron tailing powder - desulfurization ash mine filling cementitious material. *Anhui University of Technology., 1*, 1.
Chen, J. H., Yuan, Y. X., Zhu, Q., & Duan, J. Y. (2023). High-temperature resistance of high-strength concrete with iron tailing sand. *The Journal of Building Engineering., 63*(01), 105544. https://doi.org/10.1016/J.JOBE.2022.105544
Chen, X. Y. (2015). The experimental study on shear performance of green tailings concrete beam. *Industrial Safety and Environmental Protection., 41*(06), 43–47.
Chen, X. Y. (2017). Experimental study on the mechanical properties of the iron tailings sand green concrete members. *Wuhan University of Technology., 1*, 1.
Chen, X., Yu, F., & Cao, Y. (2023). Preparation and properties of iron tailings powder-desulfurization ash cementitious material. *Bulletin of the Chinese Silicate Society., 42*(1), 180–7.
Cheng, Y. H., Huang, F., Li, W. C., Liu, R., Li, G. L., & Wei, J. M. (2016). Test research on the effects of mechanochemically activated iron tailings on the compressive strength of concrete. *Construction and Building Materials, 118*(08), 164–170. https://doi.org/10.1016/j.conbuildmat.2016.05.020
Cheng, Y. H., Huang, F., Qi, S. S., Li, C., & Li, G. L. (2020). Durability of concrete incorporated with siliceous iron tailings. *Construction and Building Materials, 242*, 118147. https://doi.org/10.1016/j.conbuildmat.2020.118147
Chinnappa, B. G., Karra, C. R. (2020) Experimental and statistical evaluations of strength properties of concrete with iron ore tailings as fine aggregate. J Hazard Toxic Radio. 24 (01): 04019038–04019038. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000480
Deng, C. S., & Xia, Y. (2010). The experiment study of ore tailings sand in high-flow concrete. *Minerals and Metallurgical Engineering., 30*(01), 9–12.
Deysel, R. C., Boshoff, W. P., & Smit, M. S. (2023). Implementing capillary pressure control measures to prevent plastic shrinkage cracking in concrete. *Construction and Building Materials, 397*, 132407. https://doi.org/10.1016/j.conbuildmat.2023.132407
Duarte, M. S., Almada, B. S., & Santos, W. J. (2022). Influence of mechanical treatment and magnetic separation on the performance of iron ore tailings as supplementary cementitious material. *Journal of Building Engineering., 59*(11), 105099. https://doi.org/10.1016/J.JOBE.2022.105099
EN 12620. (2008) Aggregates for concrete - Part 1: Specification and conformity. European Committee for Standardization (CEN), Brussels, Belgium.
EN 1994–1–1. (2004) Eurocode 4: Design of composite steel and concrete structures - Part 1–1: General rules and rules for buildings. European Committee for Standardization (CEN), Brussels, Belgium.
Feng, X. X., Kang, Z. H., Bai, R. Y. (2013) Study on Basic properties of iron tailings sand and gravel. Concr. and Cem. Products Branch of Chin. Silicate Soc.
Feng, X. X., Yu, Q. Y., Liu, G., Yao, S. W. (2017) Effect of sand and gravel made from iron ore tailings on the permeability of concrete//Abstracts of the 9th International Conference on Cement Concrete.
Feng, X. X., Xi, X. L., Cai, J. W., Chai, H. J., & Song, Y. Z. (2011). Investigation of drying shrinkage of concrete prepared with iron mine tailings. *Key Engineering Materials, 1258*(477–477), 37–41. https://doi.org/10.4028/www.scientific.net/KEM.477.37
Feng, X. X., Zhao, Y., Lei, P. P., Shang, J. J., & Wang, L. Y. (2013b). Research on the Basic Properties of sand and gravel made from ironore tailing. *Proceedings of the Symposium on Concrete and Cement Products in, 2013*, 298–307.
Galvão, B. L. J., Andrade, D. H., Brigolini, J. G., Peixoto, F. A. R., & Mendes, C. J. (2018). Reuse of iron ore tailings from tailings dams as pigment for sustainable paints. *Journal of Cleaner Production, 200*, 412–422. https://doi.org/10.1016/j.jclepro.2018.07.313
GB 51032 (2014). Technical code for application of iron tailings sand concrete. China: China Planning Press.
GB/T 31288. (2014). Iron tailings sand. Standards Press of China.
GB/T50010. (2010). Code for design of concrete structures. China Building Industry Press.
Guan, P. W., Meng, H. Y., & Kuang, Z. F. (2016). Experimental research on the flexural performance of concrete beams with mine tailings sand. *New Buildings Materials., 43*(01), 18–20.
Guan, P. W., Yu, Z., & Guo, J. (2017). Experimental research on the flexural performance of concrete components with mine tailings sand. *Structural Engineers., 33*(06), 98–102. https://doi.org/10.15935/j.cnki.jggcs.2017.06.015
Gyllenram, R., Arzpeyma, N., Wei, W. J., & Jönsson, P. G. (2021). Driving investments in ore beneficiation and scrap upgrading to meet an increased demand from the direct reduction-EAF route. *Mineral Economics., 35*, 203–220. https://doi.org/10.1007/S13563-021-00267-2
Han, F. H., Li, L., Song, S. M., & Liu, J. H. (2017). Early-age hydration characteristics of composite binder containing iron tailing powder. *Powder Technology, 315*(06), 322–331. https://doi.org/10.1016/j.powtec.2017.04.022
Han, F. H., Luo, A., Liu, J. H., & Zhang, Z. Q. (2020). Properties of high-volume iron tailing powder concrete under different curing conditions. *Construction and Building Materials, 241*(04), 118108. https://doi.org/10.1016/j.conbuildmat.2020.118108
Hu, X. Y. (2015) Experimental research on inclined section shear capacity of reinforced concrete beams with tailing sand. Zhengzhou Univ.
Huang, Z. J., Zhang, Y., Ren, F. H., Zhang, L., & Guo, Q. F. (2019). Experimental analysis of influence of iron tailings sand on mechanical properties of shotcrete. *Minerals Research and Development., 39*(4), 121–126. https://doi.org/10.13827/j.cnki.kyyk.2019.04.026

Jayasimha, N., Sujini, B., & Annapurna, B. P. (2022). A study on durability and strength properties of high strength concrete with partial replacement of iron ore tailings with fine aggregates. *Materials., 65*, 1922–1929. https://doi.org/10.1016/J.MATPR.2022.05.163

Jia, X. (2013) Performance of iron mine tailing sand and its usage in concrete. Beijing Univ. of Civ. Eng. and Architecture.

Jiang, Y. F., Wang, H., Chen, Y., Ruan, M., & Li, W. (2019). Preparations of composites of composite concretes using iron tailings as fine aggregates and their mechanical behavior. *Materials Technology., 53*(04), 467–472. https://doi.org/10.17222/mit.2018.222

Kumar, G. P., & Eswanth, P. (2019). A feasibility study on the mechanical properties of concrete with iron ore tailings (IOT). *IJESC., 09*, 24050–24054.

Li, C., Yang, X. F., Li, Y. K., Chen, Y., Pan, X. D., Xie, Y. P., Liu, X. Y., & Li, S. Q. (2024). Preparation of high-purity SiO_2 by S-HGMS coupled with mixed-acid leaching, A case study on hematite tailings from Ansteel China. *Waste Manage., 174*(02), 240–250. https://doi.org/10.1016/j.wasman.2023.11.026

Li, H. Y. (2018). Experimental study on seismic bearing capacity of iron tailorite concrete column. *North China University of Science and Technology, 1*, 1.

Li, H. M., Zhang, Z. J., Li, L. X., Zhang, Z. C., Chen, J., & Yao, T. (2014). Types and general characteristics of the BIF-related iron deposits in China. *Ore Geology Reviews., 57*(03), 264–287. https://doi.org/10.1016/j.oregeorev.2013.09.014

Li, L. (2017). Study on the effect and mechanism of iron tailings powder in silicate gel system. *Beijing University of Civil Engineering and Architecture., 1*, 1.

Li, M., Zhou, Q. L., Bai, L. M., Ma, Y. X., Guan, J. G., & Yang, P. B. (2021). Experimental study on improving of activity of iron tailings by mechanochemical effect. *Multipurpose Utilization of Minerals Resources., 01*, 179–185. https://doi.org/10.3969/j.issn.1000-6532.2021.01.030

Li, S. J., & Kang, H. Z. (2018). Experimental study of axial compression behavior of ferrous tailings reinforced concrete short columns restraint by stirrup. *Concrete., 05*, 32–35.

Li, T., & Dang, B. (2016). Experimental study on the compressive strength of iron tailings concrete with different replacement types. *Hebei Journal of Industrial Science and Technology., 33*(03), 240–245.

Li, T., Wang, S. L., Xu, F., Meng, X. Y., Li, B. B., & Zhan, M. (2020). Study of the basic mechanical properties and degradation mechanism of recycled concrete with tailings before and after carbonation. *Journal of Cleaner Production, 259*(06), 120923–120923. https://doi.org/10.1016/j.jclepro.2020.120923

Li, Y. C., Liu, L., Deng, Y. F., Chen, Y. G., Li, Y. H., & Wu, J. (2023). Unlocking the potential of iron ore tailings in controlled low-strength material, feasibility, performance, and evaluation. *Journal Cleaner Production, 423*(10), 138772. https://doi.org/10.1016/J.JCLEPRO.2023.138772

Ling, J., Wang, K. P., Wang, M., Tao, Y., & Wu, T. Y. (2023). Damage evaluation of concrete using iron ore tailings as aggregates under uniaxial cyclic compression. *Granul Matter., 25*(02), 25. https://doi.org/10.1007/S10035-023-01316-Z

Liu, J. P., Ge, X. W., Liu, P., Song, G., & Hu, Z. Y. (2023). Experimental study on the preparation of cementitious materials from iron ore tailings by activation. *Construction and Building Materials, 385*, 131409. https://doi.org/10.1016/j.conbuildmat.2023.131409

Liu, K. N., Wang, S. L., Quan, X. Y., Jing, W., Xu, J., Zhao, N., & Liu, B. (2022). Effect of iron ore tailings industrial by-product as eco-friendly aggregate on mechanical properties, pore structure, and sulfate attack and dry-wet cycles resistance of concrete. *Case Studies in Construction Materials, 17*(12), e01742. https://doi.org/10.1016/J.CSCM.2022.E01472

Ma, W. H., Meng, Q. J., Kang, H. Z., Ma, Z., & Wang, Q. (2021). Experimental study on shear performance of iron tailings concrete beams. *Journal of Buildings Structures., 42*(1), 322–329. https://doi.org/10.14006/j.jzjgxb.2021.S1.0036

Ma, X. X., Sun, J. H., Zhang, R. L., Zhang, F. S., Yuan, J., & Meng, Z. L. (2024). Experimental study on flexural performance of full iron tailings concrete beam. *Journal of Architecture and Civics Engineering., 41*(03), 120–128. https://doi.org/10.19815/j.jace.2022.05051

Prema kumar, W. P., Ananthayya, M. B., & Vijay, K. (2014). Effect of replacing sand by iron ore tailings on the compressive strength of concrete and flexural strength of reinforced concrete beams. *IJERT., 3*(07), 1374–1376.

Protasio, N. M. F., Avillez, R. R. D., Letichevsky, S., & Silva, F. A. D. (2021). The use of iron ore tailings obtained from the Germano dam in the production of a sustainable concrete. *J. Clean. Prod., 278*(01), 123929. https://doi.org/10.1016/j.jclepro.2020.123929

Qin, S. T., Dou, S., Ma, S. J., Zhang, Z. J., Hu, Y., Li, Y. H., Liu, P. Z., Lin, F. J., & Zhao, H. Y. (2024). Enhanced recovery of low-grade copper ore and associated precious metals from iron tailings: A case study in China. *Colloid Surface A, 699*(10), 134656. https://doi.org/10.1016/j.colsurfa.2024.134656

Qiu, G. Q., Ning, X. N., Shen, J. H., Wang, Y., Zhang, D. Y., & Deng, J. H. (2023). Recovery of iron from iron tailings by suspension magnetization roasting with biomass-derived pyrolytic gas. *Waste Management, 156*(02), 255–263. https://doi.org/10.1016/j.wasman.2022.11.034

Radlinski, M., & Olek, J. (2015). Effects of curing conditions on properties of ternary (Ordinary Portland Cement/Fly Ash/Silica Fume) concrete. *ACI Materials Journal., 112*(1), 49–58. https://doi.org/10.14359/51687307

Rao, N. D., Chakraborty, D. P., Shukla, V., Kumar, N. (2023) Chapter 2 - Iron ore beneficiation, an overview. Miner. Process. pp. 55–77. https://doi.org/10.1016/B978-0-12-823149-4.00003-X

Shettima, A. U., Hussin, M. W., Ahmad, Y., & Mirza, J. (2016). Evaluation of iron ore tailings as replacement for fine aggregate in concrete. *Construction and Building Materials, 120*(09), 72–79. https://doi.org/10.1016/j.conbuildmat.2016.05.095

Shetty, K. K., Nayak, G., & Vijayan, V. (2014). Effect of red mud and iron ore tailings on the strength of self compacting concrete. *European Science Journal., 10*(21), 168–176.

Shi, J., Pan, W. Z., Kang, J. Y., Yu, Z. J., Sun, G. R., Li, J., Zheng, K. K., & Shen, J. Y. (2024a). Properties of ultra-high performance concrete incorporating iron tailings powder and iron tailings sand. *Journal of Building Engineering., 83*, 108442. https://doi.org/10.1016/j.jobe.2024.108442

Shi, J., Pan, W. Z., Kang, J. Y., Yu, Z. Y., Sun, G. R., Li, J., Zheng, K. K., & Shen, J. Y. (2024). Properties of ultra-high performance concrete incorporating IOTS powder and iron tailings sand. *Journal of Building Engineering., 83*(04), 108442. https://doi.org/10.1016/J.JOBE.2024.108442

Song, S. M., Zhang, L. Y., & Li, Z. Y. (2019). Effect of iron tailings micropowder on late-property of cement concrete. *Concr., 1*, 128–131.

Sun, Q. R., & Liu, L. (2020). Experimental study on carbonation resistance of concrete containing iron tailings. *Iron Steel Vanadium Titan., 41*(02), 82–88.

Sun, Y. S., Zhang, X. L., Han, Y. X., & Li, Y. J. (2020). A new approach for recovering iron from iron ore tailings using suspension magnetization roasting A pilot-scale study. *Powder Technology., 361*(02), 571–580. https://doi.org/10.1016/j.powtec.2019.11.076

Sunil, B. M., Manjunatha, L. S., Lolitha, R., & Subhash, C. Y. (2015). Potential use of mine tailings and fly ash in concrete. *Adv Concr Constr., 3*(1), 55–69. https://doi.org/10.12989/ACC.2015.3.1.055

Tang, C., Li, K. Q., Ni, W., & Fan, D. C. (2019a). Recovering iron from iron ore tailings and preparing concrete composite admixtures. *Minerals., 9*(04), 232. https://doi.org/10.3390/min9040232

Tang, K., Mao, X. S., Xu, W., & Tang, X. L. (2019). Performance analysis of cement concrete with iron tailings sand as fine aggregate. *Industrial Construction., 49*(8), 153–157. https://doi.org/10.13204/j.gyjz201908025

Tanvir, A., Mohamed, E., Basarir, H., Karrech, A., Sadrossadat, E., & Yang, B. (2021). Development of ECO-UHPC utilizing gold mine tailings as quartz sand alternative. *Clean Engineering and Technology., 04*, 100176. https://doi.org/10.1016/J.CLET.2021.100176

Tao, Y. P., & Lan, T. W. (2023). Study on mechanics and durability of iron tailings recycled concrete. *Journal of Functional Materials., 54*(03), 3143–3148.

Thomas, B. S., Damare, A., & Gupta, R. C. (2013). Strength and durability characteristics of copper tailing concrete. *Construction and Building Materials, 48*(11), 894–900. https://doi.org/10.1016/j.conbuildmat.2013.07.075

Toutanji, H. A., & Bayasi, Z. (1999). Effect of curing procedures on properties of silica fume concrete. *Cement Concrete Research., 29*(04), 497–501. https://doi.org/10.1016/S0008-8846(98)00197-5

Uchechukwu, E. A., & Ezekiel, M. J. (2014). Evaluation of the iron ore tailings from Itakpe in Nigeria as concrete material. *Advanced Materials., 3*(4), 27–32. https://doi.org/10.11648/j.am.20140304.12

Ugama, T. I., Ejeh, S. P., Amartey, D. Y. (2014) Effect of iron ore tailing on the properties of concrete. Civ. and Environmental Res. 6(10): 7–13. https://api.semanticscholar.org/CorpusID:54688713

Wang, G. Q. (2015) Experimental research on flexural behavior of reinforced concrete iron tailings. North China Univ. of Sci. and Technol.

Wang, J. H., Meng, X. Y., Li, T., Quan, X. Y., & Yan, Q. Q. (2019). Durability of recycled concrete with iron tailings sand under dry-wet cycle. *Concrete., 366*(04), 64–66.

Wang, L., Du, G. K., He, X. X., Wei, Z. C., Xu, Y. B., Li, S., & Liu, X. J. (2023). The influence of iron tailings powder on the properties on the performances of cement concrete with machine-made sand. *Coatings, 13*(05), 946. https://doi.org/10.3390/COATINGS13050946
Wang, Q. (2019). Experimental study on shear bearing capacity of concrete beams with iron tailings. *North China University of Science and Technology., 1*, 1.
Wang, R. J., Zhang, Q. J., & Li, Y. (2022). Deterioration of concrete under the coupling effects of freeze–thaw cycles and other actions A review. *Constr Build Mater., 319*, 126045. https://doi.org/10.1016/J.CONBUILDMAT.2021.126045
Wang, W. W., & Liu, H. Q. (2019). Experimental study on mechanical properties of iron tailings sand concrete after high temperature. *Non-Metallic Mines., 42*(05), 42–44.
Wang, X., Zhang, S. F., Bao, W. B., & Qi, H. J. (2020). Experimental study on durability of tailings concrete. *Concrete., 366*(04), 93–97.
Wang, Y. Y., Han, S. J., Han, X., Yuan, Y., & Zhang, H. (2018). Influence of iron tailings sand on mechanical properties of C50 concrete. *New Building Materials, 45*(08), 108–110.
Wang, Z. M., Li, Z., Jia, G. H., & Wang, L. D. (2017). Experimental study on reuse of iron ore tailings in thermal insulated glazed hollow bead concrete concrete. *Concr., 1*, 138–141.
Wu, M. (2012) Experimental study on mechanical properties of iron mine tailings self-compacting concrete. Hefei Univ. of Technol.
Xie, S. H. (2022). *Effect of iron tailing sand and fine powder on properties of cement-based materials and its mechanism*. Univ.
Xu, Y. Z. (2019) Preparation and mechanical properties of high volume iron tailings sand concrete. Shenyang Univ. of Technol.
Xu, F., Wang, S. L., Li, T., Liu, B., Li, B. B., & Zhou, Y. (2020). The mechanical properties of tailing recycled aggregate concrete and its resistance to the coupled deterioration of sulfate attack and wetting-drying cycles. *Structures., 27*, 2208–2216. https://doi.org/10.1016/j.istruc.2020.07.052
Xu, F., Wang, S. L., Li, T., Liu, B., Zhao, N., & Liu, K. N. (2021). The mechanical properties and resistance against the coupled deterioration of sulfate attack and freeze-thaw cycles of tailing recycled aggregate concrete. *Constr Build Mater., 269*(02), 121273. https://doi.org/10.1016/j.conbuildmat.2020.121273
Yang, C. M., Cui, C., & Cui, X. Y. (2014). Characteristics of the fired bricks with low-silicon iron tailings. *Construction and Building Materials, 70*(11), 36–42. https://doi.org/10.1016/j.conbuildmat.2014.07.075
Yang, L. H., Li, J. C., Liu, H. B., Jiao, H. Z., Yin, S. H., Chen, X. M., & Yu, Y. (2023). Systematic review of mixing technology for recycling waste tailings as cemented paste backfill in mines in China. *International Journal of Minerals, Metallurgy, and Materials, 30*(08), 1430–1443. https://doi.org/10.1007/S12613-023-2609-6
Yellishetty, M., & Mudd, M. G. (2014). Substance flow analysis of steel and long term sustainability of iron ore resources in Australia, Brazil, China and India. *Journal of Cleaner Production, 84*, 400–410. https://doi.org/10.1016/j.jclepro.2014.02.046
Yin, S. N., Zhang, Z. Q., & Yu, L. W. (2019). Research on mechanical property and drying shrinkage property of mortar mixed with iron tailing sand. *Bull of the China Ceram Society., 38*(6), 1707–1712. https://doi.org/10.16552/j.cnki.issn1001-1625.2019.06.011
Yu, F., Chen, X., Fang, Y., Cao, Y., Bu, S. S., & Zhang, S. J. (2024). Study on the basic properties of iron tailings powder-desulfurization ash mine filling cementitious material. *Science and Engineering of Composite Materials, 31*(1), 20240024. https://doi.org/10.1515/SECM-2024-0024
Zhang, L. S. (2015) Research on bending stiffness and crack of simply-supprted beam of iron tailing concrete. Southwest Jiaotong Univ.
Zhang, K. (2016) Experimental research on axial compression of ferrous mill tailing concrete short columns. North China Univ. of Sci. and Technol.
Zhang, G. D., Zhang, X. Z., Zhou, Z. H., & Cheng, X. (2013). Preparation and properties of concrete containing iron tailings/ manufactured sand as fine aggregate. *Advanced Materials Research., 838–841*, 152–155. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.838-841.152
Zhang, N., Tang, B. W., & Li, X. M. (2021). Cementitious activity of iron ore tailing and its utilization in cementitious materials, bricks and concrete. *Construction and Building Materials, 288*, 123022. https://doi.org/10.1016/j.conbuildmat.2021.123022
Zhang, W. F., Gu, X. W., Qiu, J. P., Liu, J. P., & Zhao, Y. Q. (2020). Effects of iron ore tailings on the compressive strength and permeability of ultra-high performance concrete. *Construction and Building Materials, 260*(11), 119917. https://doi.org/10.1016/j.conbuildmat.2020.119917
Zhang, X. Z., Fu, B. H., Liu, J. B., & Zhou, Z. H. (2014). Preparation and properties of high performance concrete based on the iron tailing mixed manufactured sand. *Concrete., 03*, 116–118.
Zhang, Y. Z., Ma, J., & Liu, H. Q. (2018). Study on durability of iron tailings concrete under the action of salt-frost cycle. *Concrete., 349*(11), 29–31.
Zhang, Z., Shrestha, A., Cai, Z. W., Ahmad, N., Yu, K. Q., & Li, L. Z. (2024). Development of high-strength engineered cementitious composites using iron sand: Mechanical and shrinkage properties. *Journal of Buildings Engineering, 95*, 110272. https://doi.org/10.1016/j.jobe.2024.110272
Zhao, J. S., Ni, K., Su, Y. P., & Shi, Y. X. (2021a). An evaluation of iron ore tailings characteristics and iron ore tailings concrete properties. *Construction and Building Materials, 286*(06), 122968. https://doi.org/10.1016/J.CONBUILDMAT.2021.122968
Zhao, J. S., Wang, Q. X., Xu, G. Q., Shi, Y. X., & Su, Y. P. (2023). Influence of macro-synthetic fiber on the mechanical properties of iron ore tailing concrete. *Construction and Building Materials, 367*(02), 130293. https://doi.org/10.1016/j.conbuildmat.2023.130293
Zhao, S. J., Fan, J. J., & Sun, W. (2014). Utilization of iron ore tailings as fine aggregate in ultra-high performance concrete. *Construction and Building Materials, 50*(01), 540–548. https://doi.org/10.1016/j.conbuildmat.2013.10.019
Zhao, Y. Q., Gu, X. W., Qiu, J. P., Zhang, W. F., & Li, X. H. (2021b). Study on the utilization of iron tailings in ultra-high-performance concrete: Fresh properties and compressive behaviors. *Materials, 14*(17), 4807. https://doi.org/10.3390/MA14174807
Zhou, H., Jiang, Y., Wang, J. Q., Zhang, H. H., Qian, B. B., Ma, B., & Hu, Y. Y. (2023). The composition and performance of iron ore tailings in steel slag-based autoclaved aerated concrete. *Buildings, 13*(12), 2942. https://doi.org/10.3390/buildings13122942
Zhu, Y. X. (2015) Experimental research on the flexural behavior of concrete slabs with tailing sand. Zhengzhou Univ.
Zhu, Z. G., Li, B. X., & Zhou, M. K. (2015). The influences of iron ore tailings as fine aggregate on the strength of ultra-high performance concrete. *Advanced Materials, 2015*, 1–6. https://doi.org/10.1155/2015/412878

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