Research Article

Experimental Study on the Performance and Microstructure of Cementitious Materials Made with Dune Sand

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This paper presents the results of an investigation on the utilization of dune sand from waterway regulation engineering as the main raw materials to produce cementitious materials. The mechanical and durability properties of the cementitious materials were studied. Furthermore, a scanning electron microscope (SEM) and mercury intrusion porosimeter (MIP) were used to identify the microstructure of the specimens. The results show that the compressive and splitting tensile strength of cementitious materials can be improved due to the addition of ground granulated blast-furnace slag (GGBS) which mainly attributes to a better grain size distribution and pozzolanic effect compared to the specimen added cement alone. The specimen with the addition of suitable cement, GGBS, and gypsum shows low dry shrinkage and excellent abrasion resistance. Correspondingly the specimens present a lower porosity and total volume of pores at different curing ages. The SEM observation indicates that there are quite a lot of hydrate products such as calcium silicate hydrate gel in the matrix which verifies the formation of cementitious compounds. The results obtained suggest that there is potential in manufacturing cementitious material with dune sand in substitution of ordinary concrete to use in hydraulic engineering.

1. Introduction

There is an abundance of very fine natural sand known as dune sand mainly distributed in coastal rivers and desert areas [1, 2]. It is quite difficult to applicate dune sand in civil engineering because of its features of poor gradation, low strength, looseness, ease of erosion, and the poor overall stability [3, 4]. Furthermore, in some dredging and waterway regulation engineering such as bank protection and slope cutting, a considerable amount of dune sand has been generated. The disposal of this huge waste sand poses a serious problem in terms of land use and potential environmental pollution. Thus, it is important to find new uses to develop the necessary technology for new processes to address this waste and to take advantage of these processes to reduce the environmental impacts of engineering projects. Utilization of the dune sand to make cementitious materials and its application in civil engineering, such as substituting ordinary concrete to produce ballast block used in hydraulic engineering, can reduce land taking and avoid transportation and pollution of waste

soil, which would create high economic and environmental benefits.

In order to meet the requirements of engineering construction using local resources and reducing the transportation costs, many research works have been conducted to use dune sand as a fine aggregate to make concrete, especially in desert regions [5–7]. The fineness modulus of dune sand is usually less than 1.5 or the average particle size is less than 0.25 mm which belongs to superfine sand [3]. The concrete with the dune sand as a fine aggregate is usually regarded as having low workability and low ductility, although it has certain economic advantages. Zhang et al. [8] used the Teng-geli and Maowusu dune sand as fine aggregate to produce concrete. The result showed that the sand/gravel ratio was controlled in the range of 28–32%. The concrete with no additives showed poor workability and small slump. Al-Harthi et al. [9] investigated the performance of concrete made with Oman dune sand partially introduced (10–100%) as fine aggregate. The results showed that the workability improved and the strength of the concrete decreased with the increase

in dune sand replacement. Alhozaimy et al. [10] carried out the study on the properties of the high strength concrete using the dune sand under normal and autoclaved curing. Results showed that it was possible to use the dune sand as a 30% partial cement replacement under autoclaved curing. Lou et al. [11] investigated the performance of concrete using dune sand from the Australian desert as fine aggregate. It was found that the compressive strength of the dune sand concrete was comparable to that of river sand concrete.

Furthermore, due to the scarcity of coarse aggregates and the availability of a large amount of dune sand in some regions, there has been a growing interest in the utilization of dune sand to make sand concrete or mortar [12–16]. Sand concrete is a fine concrete where coarse aggregate is replaced by sand and fine aggregate is replaced by filler material [17]. Bédérina et al. [15] investigated the sand concrete made with local dune sands. Results showed that the compressive strength of the dune sand concrete could reach 16.0 MPa when the cement content was 350 kg/m³ and filler content was 200 kg/m³. Bouziani et al. [14] dealt with the effect of dune sand on the properties of flowing sand concrete (FSC) mixed with different proportions of river and dune sand. The results showed that FSC had good fluidity and a better performance in terms of compressive strength at 28 days when dune sand content was about 10% by mass of total sand. Zhang et al. [8] tested the performance of mortar made with Tenggei and Maowusu dune sand. The result indicated that desert sand could be used as a fine aggregate in mortar for general civil engineering.

The brief review shows that the current main application of dune sand is used as fine aggregate in concrete mixtures. The studies on the utilization of dune sand to make sand concrete or mortar have been carried out. However, the main attention of these researches was given to the mechanical properties of the cementitious materials and attempting to substitute ordinary concrete. Very few studies focus on the potential application of cementitious materials made with dune sand in hydraulic engineering. The information about the durability of this cementitious material such as dry shrinkage or abrasion resistance is very limited. The studies on the microstructure of the cementitious materials such as pore size distribution and porosity are also very limited. Therefore, more studies need to be carried out in these aspects.

This study aims to utilize dune sand as alternative sand for the preparation cementitious materials in substitution of ordinary concrete to use in hydraulic engineering. The present work focuses on the effect of the content of cement, ground granulated blast-furnace slag (GGBS), and gypsum on the performance of cementitious materials made with dune sand, such as compressive and splitting tensile strength, drying shrinkage, abrasion resistance, and microstructure. The main purposes are to (1) investigate the compressive and splitting tensile strengths of cementitious materials, (2) analyze the durability of cementitious material through drying shrinkage and abrasion resistance tests and evaluate their potential utilization in hydraulic engineering, and (3) verify the formation of cementitious compounds and analyses of

TABLE 1: Properties of OPC, GGBS, and dune sand.

	Item		
	Cement (OPC)	GGBS	Dune sand
Chemical composition (wt%)			
CaO	62.25	37.04	8.76
SiO ₂	19.28	32.90	65.63
Al ₂ O ₃	6.77	15.36	12.63
Fe ₂ O ₃	3.47	2.46	3.42
MgO	2.68	10.18	4.52
Na ₂ O	1.18	1.12	1.83
K ₂ O	0.36	0.15	1.87
SO ₃	1.64	0.08	0.06
TiO ₂	—	—	0.58
Loss on ignition	—	0.38	—
Physical properties			
Specific gravity (g/cm ³)	3.10	2.84	—
Specific surface (m ² /kg)	385	425	—
Fineness modulus	—	—	0.85
Initial setting time (min)	90	—	—
Final setting time (min)	185	—	—
Mineralogical composition (wt%)			
C ₃ S	51.69	—	—
C ₂ S	16.35	—	—
C ₃ A	12.07	—	—
C ₄ AF	10.54	—	—

pore size distribution of cementitious materials by SEM and MIP techniques, respectively.

2. Materials and Methods

2.1. Materials

2.1.1. Cement. In this study, Ordinary Portland Cement was obtained from the Conch Cement Pty. Ltd., China. The chemical compositions determined according to BS EN 197-1:2011 and the properties of OPC are presented in Table 1.

2.1.2. Mineral Admixture. In this study, GGBS supplied by a construction company located in the Nanjing of China was used as mineral admixture. GGBS used comply with BS 6699:1992. The chemical compositions and physical properties of GGBS are illustrated in Table 1.

2.1.3. Gypsum. The gypsum used was industrial products provided by JiuYi Pty. Ltd. in Shanghai, China. The content of Ca₂SO₄·2H₂O in the gypsum is about 85.0%.

2.1.4. Admixture. A polycarboxylate high range water reducing superplasticizer (SP) in liquid conforming to the GB8076-2008 was used. The product meets GB8076-2008 standard.

FIGURE 1: The studied dune sand at the revetment of Yangtze River.

FIGURE 2: Grain size distribution of the studies dune sands.

The active ingredients of SP are more than 97% and with 7-8 pH value.

2.1.5. Fine Aggregate. The dune sand sample shown in Figure 1, which was collected from a typical bank slope of the Yangtze River in China, was used as fine aggregate. The grain size distribution of the dune sand was determined using the dry sieve analysis method and presented in Figure 2. The dune sand exhibits a uniform structure with about 90% grain sizes ranging between 0.08 and 0.3 mm. The chemical composition of the sand is presented in Table 1. It can be seen that the main compositions of dune sand are SiO_2 , Al_2O_3 , and CaO . There are no toxic ingredients and heavy metals such as Cd, Cr, and Zn in the dune sand. The mineralogical composition of the dune sand was determined by X-ray diffraction (XRD) analysis tested by UltimaIV made in Japan. The main minerals are 3% quartz, 18% feldspar, 17% amphibole, 13% chlorite, 10% water mica, 5% vermiculite, and 3% dolomite.

2.2. Mix Proportions. In this study, equivalent substitution method was used to design mixing proportions. For all mixtures, SP was added in proportion of 0.5% by weight of binder. The mixing proportions of samples are given in Table 2.

2.3. Preparation and Curing Conditions of Samples. The dune sand, GGBS, cement, and gypsum were initially mixed dry in a mixer for about 2 minutes until they were homogenous throughout. Then, the entire amount of mixing water with the SP was added and the mixing process lasted for another 3 minutes, leading to a total mixing period of 5 minutes. Finally, the fresh mixed materials were cast in the molds and vibrated by a mechanical vibrating table for 2-3 min. After that, the specimens produced were cured in air at $20 \pm 2^\circ\text{C}$ in molds covered by a polyethylene film to prevent moisture loss. After 24 h, the samples were removed from the molds and transferred to a standard condition with $T = 20 \pm 2^\circ\text{C}$ and $\text{RH} = 95 \pm 5\%$ until the testing age. In this study, every test result consists of the average of three replicate tests except one sample for the pore structure test.

2.4. Testing Methods

2.4.1. The Fresh Properties Test. The workability of the fresh cementitious materials was indicated by the slump flow (by flow table) of the material measured by a slump test according to EN 1015-3. The air content of the fresh cementitious material was tested according to Chinese National Standard GJ/T70-2009 method and the density of the freshly cementitious material was determined using ASTM C138/C138 M-14.

2.4.2. Compressive and Splitting Tensile Strength. The compressive and splitting tensile strength of the cube specimens with side lengths of 100 mm were tested according to GB/T 50081-2002, at the curing periods of 7, 28, and 90 days, respectively.

2.4.3. Drying Shrinkage. The drying shrinkage test of mortar was conducted on three $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$ prismatic specimens according to GB/T 50081-2002 method. The initial lengths of the mortar bars were measured after curing in the laboratory for 24 h. Then, the mortar samples were conveyed to a drying chamber with a temperature of $20\text{--}25^\circ\text{C}$ and a relative humidity of 50–55% until further measurements at 1, 3, 7, 14, 21, 28, 42, and 56 days.

2.4.4. Abrasion Resistance. The abrasion resistance of the mortar specimens was tested according to ASTM C 1138/97 (an underwater method). Three $\phi 300 \text{ mm} \times 100 \text{ mm}$ cylinder specimens were used for the abrasion resistance test. The specimens were abraded by underwater steel balls for a period of 72 hours. The weight loss and the abrasion resistance strength of the specimens were used to evaluate the abrasion resistance properties of specimens.

2.4.5. Microstructure Analysis. SEM analysis was carried out on C4 mix, cured for 7 and 28 days separately, which were sampled from cube samples dried in an oven at 40°C . The microstructure of the sample was tested by JSM-5900 SEM made by JEOL in Japan. And the pore size distribution and the porosity of the specimen were tested by PoreMaster GT-60 MIP produced by Quantachrome, USA.

TABLE 2: Mixing proportions of samples by weight and the mix code.

Code	Sand (kg/m ³)	Cement (kg/m ³)	GGBS (kg/m ³)	Gypsum (kg/m ³)	Water (kg/m ³)
C1	1415.0	450.0	—	—	225.0
C2	1408.8	365.0	85.0	—	225.0
C3	1402.6	280.0	170.0	—	225.0
C4	1397.7	235.0	170.0	45.0	225.0
C5	1392.8	190.0	170.0	90.0	225.0

3. Results and Discussion

3.1. Fresh Properties. The test results relevant to the fresh properties of cementitious materials such as the slump flow, density, and air content are presented in Table 3.

From Table 3, it can be seen that the slump flow diameter of mix of C2, C3, C4, and C5 is 136 mm, 143 mm, 142 mm, and 140 mm, an increasing of 3.03%, 8.33%, 7.57%, and 6.06% in comparison to the slump flow diameter of the C1 mix with cement addition alone. The incorporation of GGBS into the materials increases the slump flow diameter of the cementitious materials which mainly contributes to a better particle size distribution. Fine GGBS particles fill wide pores among cement particles and reduce water requirement [18].

As noticed, air content for C2, C3, C4, and C5 mix is 13.7%, 13.2%, 12.3%, and 12.6%, which decreased to 5.5%, 8.9%, 15.2%, and 13.1% in comparison to the air content of the C1 mix with cement addition alone. The C1 mix with cement addition alone has the lowest density. When the replacement amount of GGBS increases, the density of cementitious material increases significantly. The density of specimens increases from 2.08 g/m³ to 2.12 g/m³ when the replacement amount of GGBS varies from 85.0 kg/m³ to 170.0 kg/m³. The incorporation of GGBS contributes to a better grain size distributions and compactness which resulted in a higher density of specimens.

3.2. Compressive Strength Development. Figure 3 illustrates the strength development of the mixes after 7, 28, and 90 days of curing. It can be seen that the compressive strength of all the mixes increases with the curing time. The presence of GGBS in the cementitious materials has a significant effect on the improvement of compressive strength. When GGBS replacement amounts are 85.0 kg/m³ and 170.0 kg/m³, the compressive strength of specimen at 28 days increases by 6.42% and 13.58%, respectively, more than that of addition of cement alone.

The improvement in compressive strength with the addition of GGBS is mainly related to a better particle size distribution which results in a higher compactness and consequently higher strength. In addition, the pozzolanic reaction of GGBS also contributes to the strength development especially for late ages, where the silica and alumina react with calcium hydroxide Ca(OH)₂ to produce calcium silicate hydrates (CSH) and calcium aluminium silicate hydrates (CASH), which play a crucial role in strength development. The formation of cementitious compounds CSH can be effectively proved by the SEM results in the later section.

FIGURE 3: Development of compressive strength of designed mixes.

For the C4 mix, when the replacement amount of gypsum is 45.0 kg/m³, the compressive strengths at 7, 28, and 90 days increase by 12.52%, 7.64%, and 6.79%, respectively, compared to the C3 mix without the addition of gypsum. However, if the replacement amount of gypsum in the mix varies from 45.0 kg/m³ to 90.0 kg/m³, the compressive strength decreases by 7.07%, 16.05%, and 19.05% at the curing periods of 7, 28, and 90 days, respectively. The addition of appropriate gypsum can promote the secondary hydration or pozzolanic reaction of GGBS which contributes to the early strength development of cementitious materials [19, 20], while too much gypsum could produce large amounts of ettringite which will cause expanded internal stress and have a negative effect on the strength of the material.

3.3. Splitting Tensile Strength Development. The results of the splitting tensile strength of specimens at the curing periods of 7, 28, and 90 days are described in Figure 4. It can be seen that the splitting tensile strengths of all the mixes increase with the curing time. The addition of GGBS increases strength of mixture effectively which contributes similarly to a better particle size distribution and pozzolanic reaction. When the replacement amount of GGBS is 85 kg/m³ and 170.0 kg/m³, the splitting tensile strengths of specimen increase by 5.21% and 17.06%, respectively, at 28 days compared with C1 mix addition of cement alone.

TABLE 3: Fresh properties of cementitious materials.

Mixture number	Slump flow diameter (mm)		Content of air (%)		Density (g/cm ³)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
C1	132	3.56	14.5	0.24	2.05	0.024
C2	136	2.16	13.7	0.36	2.08	0.029
C3	143	3.27	13.2	0.14	2.12	0.014
C4	142	2.94	12.3	0.29	2.10	0.016
C5	140	2.16	12.6	0.28	2.07	0.022

FIGURE 4: Development of splitting tensile strength of designed mixes.

For the C4 mix, the splitting tensile strengths at the curing periods of 7, 28, and 90 days increase by 5.22%, 10.12%, and 8.17%, respectively, compared to the C3 mix without gypsum added, due to the addition of 45 kg/m³ gypsum. Similarly, when the replacement amount of gypsum varies from 45 kg/m³ to 90 kg/m³, the splitting tensile strengths at the curing periods of 7, 28, and 90 days decrease by 13.71%, 15.44%, and 20.32%, respectively.

3.4. Drying Shrinkage Development. Benaissa [21] found that the shrinkage property of cementitious material made with superfine sand was much higher than that of conventional concrete. Therefore, it is essential and meaningful to carry out the shrinkage properties test of the cementitious material made with dune sand. The dry shrinkage test results are described in Figure 5. It can be seen that the drying shrinkage of all specimens increased immediately at an early age and tended to stabilize with increases in curing time. It was found that the drying shrinkage of all blended cementitious material containing GGBS and gypsum materials was lower than that of adding cement alone. When the replacement amount of GGBS is 85 kg/m³ and 170 kg/m³, the dry shrinkage decreases by 7.58% and 12.87%, respectively, compared with C1 mix addition of cement alone at 1 day. A swelling effect occurred

FIGURE 5: Development of dry shrinkage of designed mixes.

with the addition of gypsum resulting in a significant reduction in the drying shrinkage of the C4 mix, even an obvious expansion for C5 mix. When replacement amount of GGBS and gypsum is 170 kg/m³ and 45 kg/m³, the dry shrinkage decreases by 56.15% and 51.22% compared with C1 mix at 1 day and 28 days, respectively.

Drying shrinkage is a paste property, a volumetric contraction of hardened cementitious material. Results from SEM combined with MIP in later sections reveal that GGBS particles present a pore refining effect on cementitious material specimens, which results in much denser microstructure and lower shrinkage value.

3.5. Abrasion Resistance. Figure 6 shows the abrasion resistance test results, indicating that the addition of GGBS and gypsum improves the abrasion resistance of specimens. When the replacement amount of GGBS and gypsum is 170 kg/m³ and 45 kg/m³, the weight loss and abrasion resistance strength of C4 mix are 6.65% and 24.01 h·m²/kg, respectively. Compared with the C1 mix addition of cement alone, weight loss of C4 mix decreases by 31.23% and its abrasion resistance strength increases by 45.43%. Sadegzadeh et al. [22] have pointed out that abrasion resistance was determined by the pore structure. As mentioned above, the addition of

FIGURE 6: Abrasion resistance test results of the cementitious materials.

GGBS particles presented a pore refining effect on cementitious material specimens by improving particle size distribution and pozzolanic reaction thereby enhancing abrasion resistance properties. The test by Galvão et al. [23] verified that the cementitious materials reinforced with polymer showed about 5.04–7.46% mass loss after the same abrasion-erosion test. When this material was utilized to repair dam surfaces, there were no edges or deleterious actions (erosion-abrasion) caused by the environment or the water flow in the flowing periods of the barrage's reservoir occurring after one year. This indicated that the C4 mix with a weight loss of 6.65% presents excellent abrasion resistance and can be used in hydraulic engineering.

3.6. Microstructure Analysis. The SEM technique was used in this study to explain the hydrate mechanism of cementitious materials made with dune sand. Figure 7 shows the SEM images of the microstructure of the C4 mix at the curing age of 7 and 28 days. Figures 7(a) and 7(c) indicate that the microstructure of cementitious material is quite dense especially at 28 days which can be explained by the substantial reduction of void areas as a result of hydration reactions. Various hydrate products such as CSH gel, $\text{Ca}(\text{OH})_2$, and ettringite at matrix revealed the presence of various cementation compounds in the dune sand matrix and verified the formation of cementitious compounds. These hydrated compounds have a significant effect on strength development. At 7 days, tabular $\text{Ca}(\text{OH})_2$, cotton-shaped C-S-H gels, and needle ettringite intertwined and overlapped each other to generate a stable structure of paste. At 28 days, the pores are filled with the needle bar shaped ettringite and C-S-H gel which make up the structure defects gradually. Structures become denser compared with the specimens at early age, which shows that the strength of the specimen increases.

3.7. Pore Size Distribution and Porosity. In this section, the pore structures of cementitious materials with different contents of GGBS and gypsum at curing periods of 7 and 28

days are discussed and shown in Table 4. Three characteristic ranges of pore sizes are identified: <10 nm, 10–100 nm, and >100 nm. According to the study by Wu and Lian [24], pores with sizes smaller than 10 nm are harmless pores, between 10 nm and 100 nm are minor harmful pores, and bigger than 100 nm are harmful pores.

It can be seen that both the total pore volume and porosity of specimens decrease with curing time. The porosity of the C4 mix with 170 kg/m^3 GGBS and 45 kg/m^3 gypsum addition decreases from $0.0878 \text{ cm}^3/\text{cm}^3$ at 7 days to $0.0657 \text{ cm}^3/\text{cm}^3$ at 28 days. And the C4 mix presents the lowest total pore volume and porosity. Compared with the C1 mix addition of cement alone, the porosity of C4 mix decreased by 19.58% at 28 days.

Furthermore, the pore size distribution of cementitious materials also changes. On the one hand, the pores become finer with the addition of GGBS and gypsum. Compared with C1 mix, the mix with the GGBS addition has more harmless pores and minor harmful pores. For example, the harmless pore (<10 nm) of the C4 mix is 15.64%, while the harmless pore of C1 mix addition cement alone is 11.23% at 28 days. This result is in agreement with the results of compressive strength, which provides evidence that the presence of GGBS improves the strength of cementitious materials. Furthermore, Uchikawa et al. [25] have shown that adding mineral powder in concrete reduces the size of hydration products, inhibits the deposit of $\text{Ca}(\text{OH})_2$ by virtue of their filling role, and, consequently, decreases pore size.

4. Conclusions

The experimental study on the performance evaluation and microstructure of cementitious materials made with waste dune sand from the waterway regulation engineering reveals the following conclusions:

- (1) The compressive and splitting tensile strength reach 32.4 MPa and 2.72 MPa, respectively, at 28 days when the replacement amount of GGBS and gypsum is 170 kg/m^3 and 45 kg/m^3 , respectively. The compressive and splitting tensile strength of cementitious materials can be improved due to addition of GGBS, which mainly attributes to a better grain size distribution and pozzolanic effect compared to the specimen adding cement alone.
- (2) The specimen addition of appropriate cement, GGBS, and gypsum shows low dry shrinkage and excellent abrasion resistance properties. When the replacement amount of GGBS and gypsum is 170 kg/m^3 and 45 kg/m^3 , the weight loss and abrasion resistance strength of specimens are 6.65% and $24.01 \text{ h}\cdot\text{m}^2/\text{kg}$, respectively, which presents an excellent abrasion resistance.
- (3) SEM observation indicates that there are quite a lot of hydrate products such as CSH gel and ettringite in the matrix which verifies the formation of cementitious compounds. The MIP results indicate that the cementitious material addition of the GGBS and gypsum

FIGURE 7: Scanning micrographs of cementitious materials: (a) 7 days $\times$ 100, (b) 7 days $\times$ 5000, (c) 28 days $\times$ 200, and (d) 28 days $\times$ 5000.

TABLE 4: Pore size distribution of the cementitious materials.

Mixture number	Age (d)	Pore size distribution						Total pore volume	Total porosity
		<10 nm		10~100 nm		>100 nm			
		cm ³ /cm ³	%	cm ³ /cm ³	%	cm ³ /cm ³	%		
C1	7	0.0039	7.97	0.0118	24.12	0.0334	67.91	0.0492	0.1018
C3	7	0.0042	9.23	0.0120	26.22	0.0290	64.55	0.0459	0.0950
C4	7	0.0053	12.38	0.0121	28.62	0.0249	59.00	0.0422	0.0878
C1	28	0.0044	11.23	0.0118	30.01	0.0228	58.12	0.0393	0.0817
C3	28	0.0048	13.21	0.0114	31.65	0.0203	56.14	0.0362	0.0753
C4	28	0.0049	15.64	0.0104	32.98	0.0167	52.78	0.0316	0.0657

presents lower porosity and total volume of pores at different curing ages compared with the specimen addition of cement alone.

The results obtained suggest that there is potential in manufacturing cementitious material with waste dune sand in substitution of ordinary concrete to use in hydraulic engineering. In addition, the effective use of waste dune sand contributes to the development of a sustainable society by reducing the huge quantity of solid waste and establishing a sound environment.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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