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Impacts of non-sieved waste construction sand under various moisture states on engineering properties of cement-based mortar

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KEYWORDS

Bulk density
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ABSTRACT

The construction industry generates a significant amount of waste, with leftover sand from masonry construction being a notable concern. This paper investigated the utilization of non-sieved waste construction sand (CS) under various moisture states to assess its impact on engineering properties of cement-based mortar. Along with the primary objective was to compare the effects of non-sieved and sieved waste CS on engineering properties of mortar. Various engineering properties of mortar were tested, including consistency of fresh mortar, bulk density, and the compressive and flexural strengths of hardened mortar specimens. Three moisture states for the waste CS were proposed, including oven-dry (OD), natural (NA), and saturated surface-dry (SSD) states. Compared to sieved waste CS, the consistency of fresh mortar with non-sieved CS increased by 14.3–66.7%. In addition, using CS in the SSD state improved the consistency by 60.0–133.3% and 23.3–27.2% compared to that in OD and NA states, respectively. Moreover, the difference in the bulk density of mortar specimens was insignificant, regardless of the moisture states of the waste CS. In terms of mechanical properties of mortar at 28 days, the results showed a reduction in compressive strength (27.0–32.3%) and flexural strength (32.2–36.4%) of mortar specimens using non-sieved waste CS compared to those using sieved waste CS, independent of the moisture states of the CS. Furthermore, using waste CS in the SSD state improved the mortar strengths when compared to that in other moisture states (OD or NA state). Additionally, a linear correlation was observed between compressive and flexural strengths of the mortar, regardless of types and moisture states of the waste CS. In conclusion, the use of non-sieved waste CS led to a reduction in mechanical strengths of hardened mortar while increasing the consistency of fresh mortar, irrespective of the moisture states of the waste CS. Utilizing the waste CS in the SSD state proved to be an effective method for enhancing the consistency of fresh mortar, and mechanical strengths of cement-based mortar compared to that in other moisture states.

1. Introduction

The construction industry has a significant growth in recent years, leading to a surge in the demand for natural resources such as river sand and crushed stone. According to Lai et al. [1], 236 million cubic meters of sand are collected from the lake each year in China. This has negative impacts, including reduced water levels, increased drought risk, and deep outflows channel of the lake. In Vietnam, unregulated mining of sand has become a national issue that requires a solution [2]. This led to the exploration of alternative materials, namely foundry sand, coal bottom ash, fly ash, and so on [3]. Some researchers have explored the concept of utilizing waste resources as substitutes for river sand in mortar. Ledesma et al. [4] investigated the effect of recycled sand from masonry waste on the performance of fresh and hardened mortars, and found that workability of fresh mortar, and bulk density and mechanical strengths of mortar decrease linearly with the replacement level of recycled sand. Silva et al. [5] suggested that substituting natural sand with crushed burnt clay waste from a brick factory affects mechanical properties of the cement-based mortar, namely flexural and compressive strengths of mortar which are improved, within a 50% replacement limit. However, replacing natural sand with waste resources still presents several challenges that have a negative impact on the properties of both fresh and hardened mortars.

On the other hand, several studies have pointed out that moisture states and particle size distribution of aggregate influence the characteristics of both mortar and concrete [6-11]. Teo and Lee [8] concluded that moisture presence in oil palm shell, which obtained from palm oil extraction, affects slump and mechanical strengths of concrete. Using aggregates under saturated surface-dry (SSD) state is more effective in producing high-strength concrete compared to those under air-dry and sun-dry states, even though the mixture using aggregate under SSD state has the lowest slump [8]. Santos et al. [9] investigated the mechanical behavior of cement-based mortar using five different grain size of sand and explored that the smaller size of sand enhances the mechanical performance of mortar by filling the voids between the

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coarse aggregate, resulting in better cohesion between the aggregate and cement matrix. Pipilikaki and Beazi-Katsioti [10] determined that the size distribution of limestone in the cement pastes affects the pore structure of the hardened blended cement concretes, through the filling effect of the limestone powder. Furthermore, Alhozaimy [11] found that concrete with limestone aggregates under dry condition had a higher slump and a lower compressive strength than that with aggregates under wet condition. Therefore, moisture states and particle size of the aggregate have a significant impact on the overall performance of mortar and concrete.

Meanwhile, the urbanization rate in Vietnam was predicted to reach 45 % by 2026, resulting in the emergence of numerous construction sites which create construction waste and cause environmental issues in urban areas [12]. One of the structural wastes is residual sand (i.e., sand retained on the 5-mm sieve), which accounts for approximately 4 % of the total sand amount used for building. As a result, leftover sand from construction sites should be recycled and utilized to make mortar or concrete to minimize pollution and reduce the pressure on the exploitation of natural resources. Lastly, there has been a limited number of studies in Vietnam that specifically explore the use of this waste sand sourced from construction sites as well as the effect of moisture states of such sand on properties of cement-based mortar, leading to the initiation of the present research.

Hence, this study aims to introduce and explore the effects of non-sieved waste construction sand (NCS) under different moisture conditions on engineering properties (including consistency, bulk density, and mechanical strengths) of mortar in comparison to those of sieved waste construction sand (SCS) as a reference fine aggregate meeting TCVN 7570:2006 [13], with the goal of finding out the variations of impacts between non-sieving and sieving processes, as well as reducing waste generated by such sand from the construction sites and promoting environmentally sustainable construction practices.

2. Experiment

2.1. Materials

In this study, blended Portland cement (PCB) with a strength grade of 40 MPa provided by Ha Tien Company was employed to create cement-based mortar specimens, satisfying with specifications listed in TCVN 6260:2020 [14]. The cement that was tested as per TCVN 4030:2003 [15] had density of 2.95 g/cm^3 and bulk density of 1276 kg/m^3. In addition, tap water that met TCVN 4506:2012 [16] was used to mix and cure the mortar specimens.

Fine aggregate used in this study was the waste construction sand (CS) taken from Ho Chi Minh city, including two types SCS and NCS as shown in Figure 1. The SCS had a fineness modulus of 1.75 because of treatment process through a 5-mm sieve. Meanwhile, the NCS originated from CS without any treatments possessed a fineness modulus of 2.54. The physical properties of SCS and NCS are given in Table 1, whereas Figure 2 depicts the particle size distribution curves of fine aggregates. The results showed that CS in the SSD state had higher density and bulk density when compared to that in the NA and OD states, regardless of whether CS was sieved or not. Furthermore, the particle size distribution of SCS met the standard of TCVN 7570:2006 [13], as opposed to NCS. To investigate the influence of moisture states of CS on engineering properties of cement-based mortar, three moisture states of CS including natural (NA), oven-dry (OD), and SSD were employed. The moisture contents of SCS and NCS were 3.19 % and 2.85 %, respectively, while their water saturation contents corresponded to 5.68 % and 4.33 %. Two moisture states (OD and SSD) of the CS were determined based on a shape after lifting the mold as per TCVN 7572-4:2006 [17], expected for CS in the NA state.

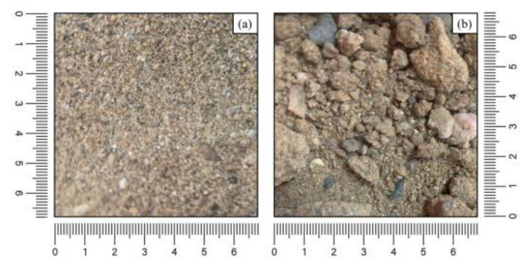

Figure 1. Tested sand: (a) SCS and (b) NCS.

Table 1. Physical properties of SCS and NCS under three moisture states.

Aggregate type	Density (g/cm^3)			Bulk density (kg/m^3)		
	SSD	NA	OD	SSD	NA	OD
SCS	2.65	2.66	2.64	1430	1409	1400
NCS	2.67	2.64	2.62	1400	1404	1398

SCS: sieved waste construction sand; NCS: non-sieved waste construction sand;
SSD: saturated surface-dry state; NA: natural state; OD: oven-dry state.

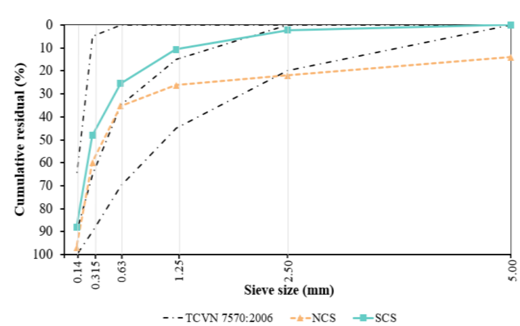

Figure 2. Particle size distributions of of NCS and SCS.

2.2. Mixture proportions

All mortar mixture proportions were established with a water-to-cement ratio (W/C) and fine aggregate-to-cement ratio corresponding to 0.5 and 3, respectively. These proportions were selected based on

TCVN 6016:2011 [18] as well as previous research by Bentlemsan et al. [19], Ghania et al. [20], de Matos et al. [21]. Detailed mixture compositions for each mortar mixture proportion can be found in Table 2. Notably, the water content presented in Table 2 did not include the moisture content and water absorption of the materials.

Table 2. Mixture proportion of all the mortar.

Mixture proportion ID	W/C	Unit (kg/m^3)			
		Cement	SCS	NCS	Water
NA-RC	0.5	509	1524	0.0	255
OD-RC	0.5	506	1520	0.0	253
SSD-RC	0.5	507	1523	0.0	254
NA-NRC	0.5	506	0.0	1520	253
OD-NRC	0.5	504	0.0	1513	252
SSD-NRC	0.5	510	0.0	1528	255

W/C: water-to-cement ratio;
SCS: sieved waste construction sand;
NCS: non-sieved waste construction sand;
RC: cement-based mortar containing SCS;
NRC: cement-based mortar containing NCS;
NA: natural state; OD: oven-dry state; SSD: saturated surface-dry state.

2.3. Mixing, specimen casting, and curing condition

The specimen preparation process was carried out in the following steps. Aggregates under OD condition were prepared through a drying process in a dry oven while those under SSD condition were prepared through a water immersion process and thereby air drying until reaching the shape after lifting the mold as per TCVN 7572-4:2006 [17] (Figure 3). After that, the raw materials were measured using a technical balance according to each mixture proportion as shown in Table 2. An automatic mortar mixer was used to mix cement and water for 30 seconds at a low speed. Next, sand (either SCS or NCS) was added to the mixer and mixed for an additional 2 minutes at a high speed to create a uniform fresh mortar. The consistency of the fresh mortar was tested using the method outlined in section 2.4.1. The fresh mortar was then packed into the mold compartments and compacted 60 times for each layer using a jolting apparatus. Afterward, the molds were wrapped in polyethylene sheets to prevent water evaporation. After demolding, the hardened mortar specimens were cured in a water tank at 27 ± 2 °C until the required ages.

Figure 3. The shape of the aggregate under the (a) OD and (b) SSD states.

2.4. Test procedure

2.4.1. Consistency of fresh mortar

Fresh mortar was poured into the truncated conical mold in two increments once all the ingredients had been thoroughly mixed. The mold was then positioned in the center of a disc of a flow table. A steel rod was used to compact the fresh mortar inside the cone by 10 times after next layer was applied. The mold was then carefully lifted up vertically, and the mortar on the disc flew when giving the flow table by 15 jolts. A technical ruler was used to measure diameter of mortar in two perpendicular directions. The consistency of the fresh mortar was calculated as the mean of two measurements as per TCVN 3121-3:2022 [22]. Figure 4 depicts the flow of mortar on the flow table testing apparatus.

Figure 4. Flow of mortar specimen.

2.4.2. Bulk density and mechanical strengths of hardened mortar

For assessing the hardened properties of the mortars, three prismatic (40×40×160 mm) specimens were used for each mixture proportion at each age. Various tests and measurements were conducted to investigate bulk density, flexural, and compressive strengths of hardened mortar. To assess the bulk density at 28-day ages, these specimens were weighed with a scale, and their volume were measured with a ruler following to TCVN 3121-10:2022 [23]. These prismatic specimens were subjected to three-point bending and compression tests at ages of 1, 3, 7, 28, and 56 days according to TCVN 3121-11:2022 [24]. A hydraulic pressure machine with 30 kN of bending load and 300 kN of compression capacity was used to test the specimens at loading rates of 50 N/s and 200 N/s, respectively. Figure 5 depicts the bending and compression tests for mortar specimens.

Figure 5. Testing (a) flexural and (b) compressive strength of cement mortar.

3. Results and discussion

3.1. Consistency of fresh mortar

Figure 6 illustrates the impact of CS, both SCS and NCS, at various moisture conditions on the consistency of fresh mortar, with a standard deviation between 0.00 and 3.54 %. In general, the inclusion of SCS led to a decrease in mortar flow, ranging from 12.5 % to 40.0 % compared to that of the NRC under all moisture states. This can be explained due to the lower fineness modulus of SCS (1.75) than that of NCS (2.54). These findings align with the conclusions drawn by de Matos et al. [21], Teo and Lee [8]. However, the consistency of mortar using CS in the SSD condition showed a improvement compared to that of mortar using CS in the OD and NA states, regardless of SCS or NCS. For instance, comparing the mortar using CS in OD and NA states, the flow diameter of NRC in the SSD state increased by 60.0 % and 23.1 %, respectively. This tendency is similar to the findings of Zhuang et al. [25], Francioso et al. [26]. Nevertheless, due to the low consistency of the RC sample with CS in OD state, casting such specimens was not possible. This can be explained due to the fineness modulus of SCS, and CS in the OD state which absorbed a part of mixing water, resulting in a reduction in consistency of the fresh mortar.

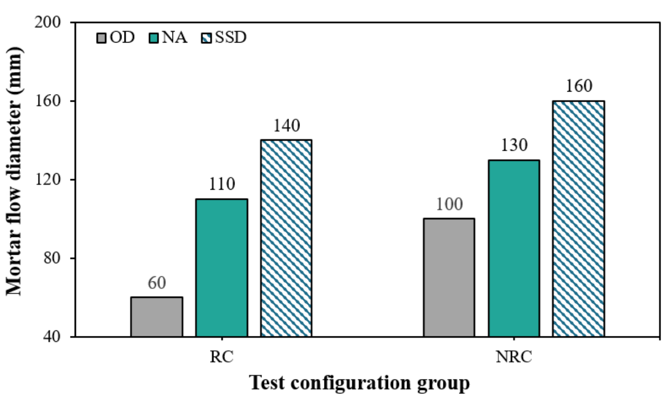

Figure 6. Consistency of fresh mortar with SCS (RC) and NCS (NRC) under various moisture conditions.

3.2. Bulk density of hardened mortar

The bulk density of hardened mortar specimens obtained after 28 days of curing is presented in Figure 7, with a standard deviation between 1.44 and 2.33 %.

The RC specimens presented slightly higher bulk density than the NRC specimens, however, the difference was insignificant (0.84 to 2.06 %), regardless of the moisture states of the CS. This can be attributed to the use of the same components as well as bulk density of various CS types which was nearly the same, irrespective of treatment process and moisture states.

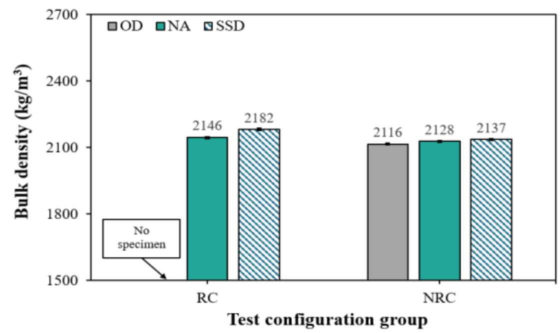

Figure 7. Bulk density at 28 days of hardened mortar with SCS (RC) and NCS (NRC) under various moisture conditions.

3.3. Flexural strength of hardened mortar

Figure 8 shows the flexural strength of cement-based mortar using SCS (RC) and NCS (NRC) under diffrerent moisture conditions. Generally, the flexural strength improved as the curing duration increased for all mortar specimens, regardless of the moisture state and types of CS. For example, the flexural strength of SSD-RC at 1-day, 3-day, 7-day and 28-day ages was lower than that at 56-day ages, and the same trend was observed for the remaining specimens. The results in the development of flexural strength were similar to the research conducted by Amritkar et al. [27], Luhar et al. [28]. This could be attributed to the formation of cement hydration products over time [27]. However, regardless of the moisture state of CS, the use of NCS decreased the flexural strength of mortar specimens at all ages when compared with that of SCS. According to the data at 28-day age, the flexural strength of NRC specimen was lower by 31.1–38.8 % than that of RC specimen. This pattern matched the findings of the Ghania et al. [20]. In this study, the reason could be due to the coarser size of NCS than that of SCS.

Meanwhile, independent of SCS or NCS, the flexural strength of the mortar specimen with CS in the SSD state was significantly higher by 9.33–69.8 % when compared to that with CS in the OD and NA states (Figure 8). According to Teo and Lee [8], the improvement was attributed to the effectiveness of internal curing provided by the aggregates in SSD state.

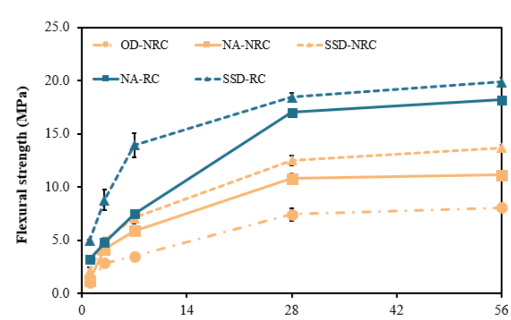

Figure 8. Flexural strength up to 56 days of hardened mortar with SCS (RC) and NCS (NRC) under various moisture conditions.

3.4. Compressive strength of hardened mortar

Figure 9 presents the development of the compressive strength of the cement-based mortars using SCS (RC) and NCS (NRC) under different moisture conditions. Similar to flexural strength, regardless of the moisture state, the compressive strength increased as the curing period increased. For instance, the compressive strength of SSD-RC was found to be increased at 56-day age when compared to that at 1, 3, 7 and 28-day ages, and this pattern was also observed for the other specimens. The findings on the development of compression strength were comparable to those of studies carried out by Montoya et al. [29], Krishna and Kumar [30]. This verified once more that cement hydration products developed over time [25].

Nevertheless, at the same moisture state of CS, there were gradual reductions in compressive strength of mortar using NCS when compared with that using SCS. As compared to RC at 28-day age, compressive strength of NRC using CS at NS and SSD states was lower by 31.1 and 34.4 %, respectively. Similar findings have been reported by Mushtaq et al. [31], Gholampour et al. [32] wherein compressive strength was significantly decreased as void increased. The decrease of compressive strength could be attributed to a combination of two factors including (1) the compaction of the mixture; (2) the excess coarse size of NCS in the mortar (Figure 2), which had the potential to settle on the surface of the aggregates and prevented the formation of bonds between these aggregates and the cement paste [33].

According to Figure 9, the compressive strength of mortar using CS at SSD state significantly enhanced by 3.9–60.1 % when compared to that using CS in the NA and OD states, regardless of sand types. For instance, the SSD-RC specimen exhibited a higher compressive strength compared to the NA-RC specimen. A related trend was observed for the compressive strength of NRC, which trended similar to the study conducted by Tong et al. [34]. According to Al-Khaiat and Haque [35], this variation was attributed to the water stored in sand particles in SSD state, which kept the cement hydration process going.

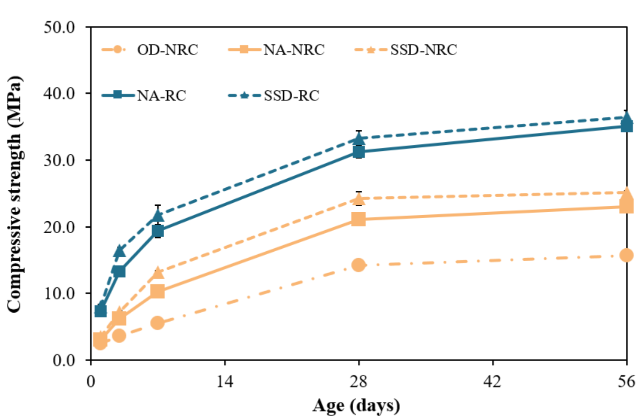

Figure 9. Compressive strength up to 56 days of hardened mortar with SCS (RC) and NCS (NRC) under various moisture conditions.

3.5. Relationship between flexural and compressive strengths of hardened mortar

Figure 10 shows the relationship between the flexural and compressive strengths of cement-based mortars. The strength of mortars using CS at different moisture conditions showed an upward trend, indicating that as compressive strength increased, the flexural strength of mortar increased. The data exhibited a strong linear relationship, with a high correlation coefficient ($R^2 = 0.9666$). Based on this result, the flexural strength was possible to make inferences from the compressive strength of cement-based mortar. These results tended to be similar to studies of Phan et al. [36], regardless of SCS or NCS.

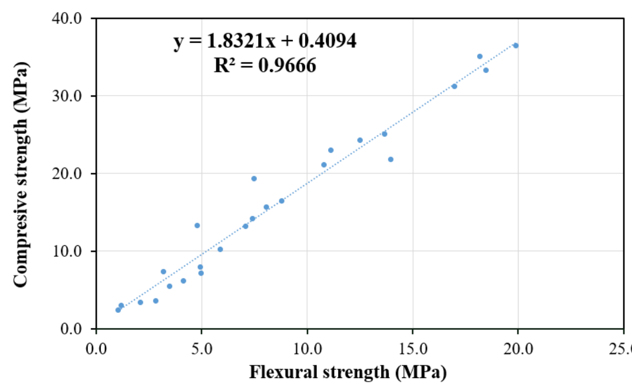

Figure 10. The relationship between flexural and compressive strengths in cement-based mortars.

4. Conclusions

The main outcomes are:

• The consistency of fresh mortar using non-sieved CS (NCS) increased when compared with that using sieved CS (SCS), regardless of the moisture states of sand. In addition, using CS in the SSD state improved the consistency by 60.0–133.3 % and 23.3–27.2 % compared to that in OD and NA states, respectively.

• The bulk density of hardened mortar was independent of the moisture states (OD, NA, and SSD) and types of CS (NCS or SCS).

• The compressive and flexural strengths of hardened cement-based mortar using NCS decreased when compared with those using SCS, regardless of the moisture states of sand.

• Regardless of CS type (NCS or SCS), the use of CS in SSD state could enhance the consistency of fresh mortar and mechanical strengths of the hardened mortar up to 56 days.

Consequently, the experimental results in the present study showed the possibilities of the application of CS from construction sites in cement-based mortar production and utilizing the waste CS in the SSD state proved to be an effective method for enhancing engineering properties of cement-based mortar, towards sustainable development for construction industry. Further studies related to mechanical performance and durability concrete using CS should be done.

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Flexural strength
Waste construction sand

ABSTRACT

The construction industry generates a significant amount of waste, with leftover sand from masonry construction being a notable concern. This paper investigated the utilization of non-sieved waste construction sand (CS) under various moisture states to assess its impact on engineering properties of cement-based mortar. Along with the primary objective was to compare the effects of non-sieved and sieved waste CS on engineering properties of mortar. Various engineering properties of mortar were tested, including consistency of fresh mortar, bulk density, and the compressive and flexural strengths of hardened mortar specimens. Three moisture states for the waste CS were proposed, including oven-dry (OD), natural (NA), and saturated surface-dry (SSD) states. Compared to sieved waste CS, the consistency of fresh mortar with non-sieved CS increased by 14.3–66.7%. In addition, using CS in the SSD state improved the consistency by 60.0–133.3% and 23.3–27.2% compared to that in OD and NA states, respectively. Moreover, the difference in the bulk density of mortar specimens was insignificant, regardless of the moisture states of the waste CS. In terms of mechanical properties of mortar at 28 days, the results showed a reduction in compressive strength (27.0–32.3%) and flexural strength (32.2–36.4%) of mortar specimens using non-sieved waste CS compared to those using sieved waste CS, independent of the moisture states of the CS. Furthermore, using waste CS in the SSD state improved the mortar strengths when compared to that in other moisture states (OD or NA state). Additionally, a linear correlation was observed between compressive and flexural strengths of the mortar, regardless of types and moisture states of the waste CS. In conclusion, the use of non-sieved waste CS led to a reduction in mechanical strengths of hardened mortar while increasing the consistency of fresh mortar, irrespective of the moisture states of the waste CS. Utilizing the waste CS in the SSD state proved to be an effective method for enhancing the consistency of fresh mortar, and mechanical strengths of cement-based mortar compared to that in other moisture states.

1. Introduction

The construction industry has a significant growth in recent years, leading to a surge in the demand for natural resources such as river sand and crushed stone. According to Lai et al. [1], 236 million cubic meters of sand are collected from the lake each year in China. This has negative impacts, including reduced water levels, increased drought risk, and deep outflows channel of the lake. In Vietnam, unregulated mining of sand has become a national issue that requires a solution [2]. This led to the exploration of alternative materials, namely foundry sand, coal bottom ash, fly ash, and so on [3]. Some researchers have explored the concept of utilizing waste resources as substitutes for river sand in mortar. Ledesma et al. [4] investigated the effect of recycled sand from masonry waste on the performance of fresh and hardened mortars, and found that workability of fresh mortar, and bulk density and mechanical strengths of mortar decrease linearly with the replacement level of recycled sand. Silva et al. [5] suggested that substituting natural sand with crushed burnt clay waste from a brick factory affects mechanical properties of the cement-based mortar, namely flexural and compressive strengths of mortar which are improved, within a 50% replacement limit. However, replacing natural sand with waste resources still presents several challenges that have a negative impact on the properties of both fresh and hardened mortars.

On the other hand, several studies have pointed out that moisture states and particle size distribution of aggregate influence the characteristics of both mortar and concrete [6-11]. Teo and Lee [8] concluded that moisture presence in oil palm shell, which obtained from palm oil extraction, affects slump and mechanical strengths of concrete. Using aggregates under saturated surface-dry (SSD) state is more effective in producing high-strength concrete compared to those under air-dry and sun-dry states, even though the mixture using aggregate under SSD state has the lowest slump [8]. Santos et al. [9] investigated the mechanical behavior of cement-based mortar using five different grain size of sand and explored that the smaller size of sand enhances the mechanical performance of mortar by filling the voids between the

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