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Influence of moisture states of recycled sand from construction sites on mechanical strengths of cement-based mortar

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KEYWORDS

Cement-based mortar
Consistency
Compressive strength
Flexural strength
Sand replacement

ABSTRACT

This study focuses on investigating the influence of moisture states of recycled sand (RS) from construction sites on properties of cement-based mortars. The major goal of this study was to utilize the amount of RS as a waste at the construction sites, as well as to reduce the burden on natural sand extraction and to save the construction cost. The use of RS as a partial replacement for natural river sand (NS) at various percentages (0% and 50% by mass of fine aggregate) was employed. Various investigations of properties including consistency of fresh mortar, compressive and flexural strengths of hardened mortar specimens, were conducted. The two moisture states for both sands were saturated surface dry (SSD) and dry state (DS). When increasing the percentages of RS replacement, regardless of the moisture states of sand, the results indicated that consistency of fresh mortar, compressive and flexural strengths at 28 days tended to decrease by 11.1–20.0%, 7.8–8.9%, and 7.4–13.8%, respectively. When compared with mortar using sand at DS state, the improvement of consistency, compressive and flexural strengths at 28 days of mortar using sand at SSD state was 20.0–33.3%, 72.2–74.3%, and 23.3–32.4%, respectively, depending on the type of sand (NS or RS). Furthermore, the correlation between compressive and flexural strengths of the mortar was linear. In conclusion, the replacement of NS by RS at 50% reduced the consistency and mechanical strengths of the cement-based mortar, while the use of RS in SSD state can be considered as an effective solution for enhancing the strengths of cement-based mortar compared to that in DS state.

1. Introduction

Concrete is the widely used as construction material in the world and is created by mixing cement, water, aggregates, and admixture (if required). However, excessive extraction of natural resources, such as river sand and crushed stone, driven by the rapid growth of industry and urbanization, has given sustainability challenges [1]. Furthermore, the increased demand for fine aggregate has led to a surge in sand mining from riverbeds, which can cause flooding, biodiversity loss in riverbed ecosystems, soil and water pollution, and other difficulties [2]. China stands as the largest consumer of sand worldwide, with an annual consumption reaching up to 20 billion tons, which constitutes roughly half of the total consumption around the world [3]. In Vietnam, the requirement of sand for building construction has risen from 92 million cubic meters in 2015 to 160 million cubic meters in 2020 [4]. As a result, the natural river sand (NS) resources are gradually depleting, and there will be a risk of sand shortages in the future. To solve this problem, many scientists have aimed at making use of waste resources as an alternative material for natural aggregate, to improve properties of mortar and concrete, with a particular emphasis on eco-friendly solutions.

Some researchers have looked at the idea of utilizing waste resources to replace NS in mortar and concrete. Moon et al. [5] used waste sand from the foundry industry, namely CO_2-silicate bonded sand (COW), as fine aggregate to replace NS in mortar and concrete. The results indicated that the partial substitution of COW reduces the bleeding rate of fresh concrete, as well as increases compressive and tensile strengths of hardened concrete. Nonetheless, as the replacement ratio of COW increases, the flow value and compressive strength of the mortar decrease rapidly. Ramadoss and Sundararajan [6] highlighted that the optimal replacement percentage of NS with coal bottom ash (BA) was in a range from 20% to 40%, without significantly effect on the compressive and flexural strengths of mortar. However, when the replacement of BA increased beyond 20%, the water absorption and air content of mortar increased. Bentlemsan et al. [7] reported that incorporating marble powder (MP) waste as a substitute for NS in self-compacting mortars enhanced the workability, strength, and reduced the porosity of the mortar. Likewise, Khyaliya et al. [8] showed that by using MP for sand replacement ranging from 25% to 50%, significant benefits can be attained, including reduced water requirement, improvements of the mechanical properties and durability of mortar compared to control mortar. Furthermore, Neno et al. [9] replaced NS with fine recycled concrete aggregate in mortar and found an

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improvement of the mechanical strength of hardened mortar. However, this substitution led to a reduction in the consistency of fresh mortar and took a lot of time and operation cost for aggregate crushing process. Based on the previous research mentioned above, replacing NS with the waste resources still presents several challenges that have a negative impact on the properties of both fresh and hardened mortar or concrete.

On the other hand, the moisture states of the aggregate affect the properties of the fresh and hardened mortar or concretes. According to Kisku et al. [10], depending on the amount of moisture in aggregate, the properties of fresh and hardened concretes with recycled aggregates were slightly lower compared to control concrete. Poon et al. [11] found when recycled aggregates under dry state (DS) were used in concrete, the results showed that the compressive strength and slump value were higher than those of concrete using saturated surface dry (SSD) recycled aggregate [11]. Based on these studies [10-11], using DS aggregate into concrete was more effective than using SSD aggregate. However, Montoya et al. [12] showed that concrete containing aggregates in the pre-saturated state has higher mechanical strengths than that containing aggregates in the DS and SSD states. Kou and Poon [13] reported that using oven-dried aggregates resulted in a higher initial slump and faster slump loss of fresh concrete when compared to air-dried and SSD aggregates. These results are similar to those of Tong [14] where recycled concrete aggregate at different moisture states was used as coarse aggregate to replace crushed stone in concrete. Nevertheless, the compressive strength of concrete with recycled concrete aggregate at the SSD state was higher than that of concrete with recycled concrete aggregate at the DS. Thus, moisture states of the aggregate have a significant impact on the overall performance of concrete.

Additionally, the urbanization rate in Vietnam was expected to reach 45% by 2026, which means multiple construction sites will emerge, leading to the generation of construction wastes, and the risks of pollution in urban areas [15]. At construction sites in Vietnam, an amount of sand is removed from construction sites before using for plastering and masonry stages. Therefore, to minimize pollution and reduce the burden on natural resource extraction, unused sand from construction sites should be recycled and applied into mortar or concrete. Lastly, few studies in Vietnam focus on the utilization of recycled sand (RS) from construction sites, which gave rise to the current study.

Hence, the aim of this study was to examine the influence of moisture states of RS from construction sites on the consistency, compressive strength, and flexural strength of hardened mortar to evaluate the practicality of utilizing RS in mortar production, with the goal of reducing waste generated by such sand from the construction sites and promoting environmentally sustainable construction practices.

2. Experiment

2.1. Materials

2.1.1 Cement and water

In this study, Portland cement blended (PCB) with a strength grade of 40 MPa was used to prepare cement-based mortar specimens. The cement supplied by Ha Tien Company met the requirements outlined in TCVN 6260:2020 [16]. The density and bulk density of the cement tested in accordance with TCVN 4030:2003 [17] were 2.95 g/cm^3 and 1276 kg/m^3, respectively. Furthermore, the mortar was mixed and cured using tap water that satisfied the standards specified in TCVN 4506:2012 [18].

2.1.2 Fine aggregate

The NS served as the natural fine aggregate, possessing a fineness modulus of 2.62. Meanwhile, after being collected from a construction site in Ho Chi Minh City, the RS was processed by passing through a 5-mm sieve, with a fineness modulus of 1.75. In this study, NS was replaced by RS at a proportion of 50% by mass, with a fineness modulus of 2.34. The physical properties of NS and RS are given in Table 1. The particle size distribution curves of fine aggregates are shown in Figure 1, meeting the standard of TCVN 7570:2006 [19]. To investigate the influence of moisture states of RS on properties of cement-based mortar, two moisture states of sand including SSD and DS were employed. These moisture states of the sand were determined based on a shape after lifting the mold as per TCVN 7572-4:2006 [20].

Table 1. Physical properties of fine aggregates.

Aggregate type	Density (g/cm^3)		Bulk density (kg/m^3)	
	SSD	DS	SSD	DS
NS	2.79	2.77	1440	1420
RS	2.65	2.64	1430	1400

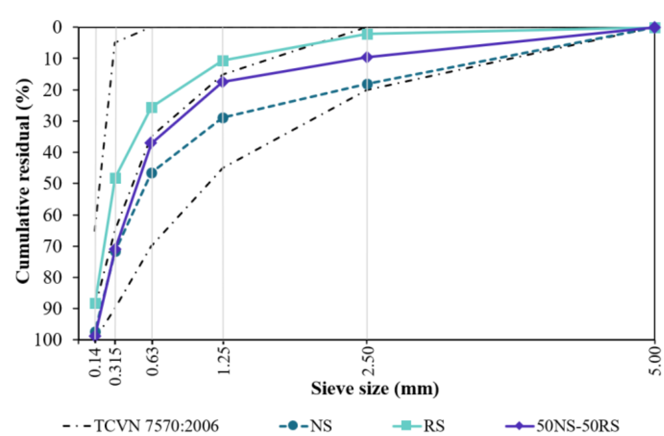

Figure 1. Particle size distributions of NS, RS, and a mixture of 50% NS and 50%RS (50NS-50RS).

2.2. Mixture proportions

A mixture proportion for the control mortar with 100% NS was determined according to TCVN 6016:2011 [21]. A consistent water-to-cement ratio of 0.5 and a fine aggregate-to-cement ratio of 3.0 were applied to all mixtures. Two different percentages of RS, namely CR0 and CR50, presented for 0% and 50% replacements of NS by RS, were used into the mixtures, respectively. These percentages were chosen based on prior studies by Bentlemsan et al. [7], Ghania et al. [22], and Matos et al. [23]. The specific mixture proportions for each percentage replacement of NS by RS can be found in Table 2. In Table 2, SSD and DS represent saturated surface dry and dry states of sand, respectively.

Table 2. Mixture proportion of all mortar specimens

Mixture proportion ID	RS replacement (% by mass)	Unit (kg/m^3)			
		Cement	RS	NS	Water
SSD-CR0	0	522	0	1567	261
SSD-CR50	50	515	772	772	257
DS-CR0	0	520	0	1561	260
DS-CR50	50	513	770	770	257

2.3. Mixing, casting, and curing condition

A procedure of specimen preparation was done within five steps as follows: (1) all the materials were carefully prepared and quantified by a technical balance; (2) after mixing cement and water for the first 30 seconds by an automatic mortar mixer at low speed, sand (RS or NS or both of them) was added to the mixer and mixed for further two minutes at high speed in order to achieve a uniform fresh mortar; (3) the consistency of fresh mortar was tested as described in section 2.4.1; (4) the fresh mortar was placed into the mold compartments and compacted 60 times for each layer using a jolting apparatus; (5) the mold were all then wrapped in polyethylene sheets for curing in 20 ± 4 hours for preventing water evaporation; (6) all the specimens were demolded and then cured in normal water condition at 27 ± 2^0C.

2.4. Test procedure

2.4.1 Consistency of fresh mortar

Once all the components were thoroughly mixed, the fresh mortar was poured into the truncated conical mold in two increments which placed centrally on the disc of the flow table. After each layer was added, the fresh mortar inside the cone was compacted 10 times using a steel rod. After that, the mold was gently lifted in a vertical manner and the mortar was spread onto the disc by giving the flow table 15 jolts. The diameter of the mortar was measured in two directions that were perpendicular to each other using a technical ruler. Subsequently, the consistency of the fresh mortar was measured as the average of two-time measurements in accordance with the guidelines outlined in TCVN 3121-3:2022 [24].

2.4.2 Flexural and compressive strengths of hardened mortar

For assessing the hardened properties of the mortars, prismatic ($40 \times 40 \times 160$ mm) specimens were used for each mixture. Various tests and measurements were conducted to investigate flexural and compressive strengths of hardened mortar. Three-point bending and compression tests were conducted on the prismatic specimens at the ages of 1, 3, 7, and 28 days following TCVN 3121-11:2022 [25]. The specimens were subjected to testing loads using a hydraulic pressure machine with capacities of 30 kN for bending and 300 kN for compression at loading rates of 50 N/s and 200 N/s, respectively.

3. Results and discussion

3.1. The consistency of fresh mortar

Figure 2 shows flow diameter of the mortars containing the different levels of RS at different moisture (DS and SSD) states. The result indicated that the increase in RS content reduced the flow diameter of the mortars, regardless of the moisture states. However, the consistency of the fresh mortar using sand in the SSD state was improved compared to that using sand in the DS state, regardless of sand types. In detail, compared with the consistency of CR0, these reductions were of 20.0% and 11.1% for CR50 using sand at DS and SSD states, respectively. This probably occurred due to the presence of fine particles of RS, as determined in the particle size analysis (see Figure 1). The fineness modulus of these particles impacted on their water adsorption, resulting in reduced flowability of the mortars as the replacement level increased. This result agreed to those found by Matos et al. [26] and Nguyen and Truong [27]. Additionally, using sand at SSD state in mortar improved the mortar flow diameter of CR0 and CR50 by 20.0% and 33.3%, respectively, compared to that using sand at DS state. The variation in consistency may be attributed to the sand at SSD state which did not absorb the mixing water in mortar [12], [14].

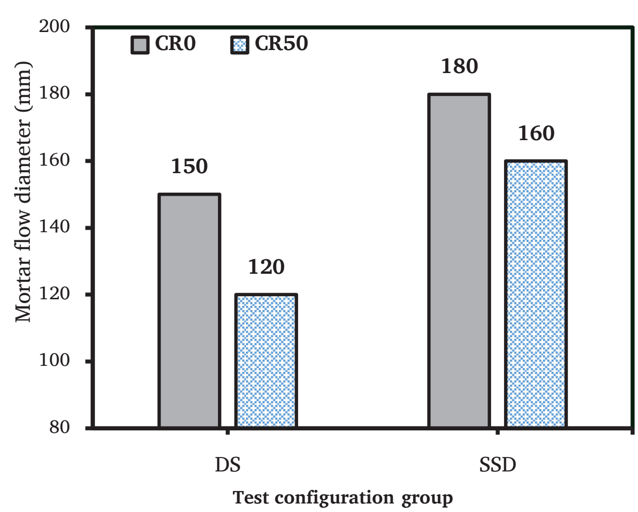

Figure 2. Influence of moisture states of sand on consistency of fresh mortar.

3.2. Flexural strength of hardened mortar

Figure 3 illustrates the progression of flexural strength for all the mortars with sand under different moisture states at various curing ages. The results obtained clearly demonstrate the flexural strength improved as the curing duration increased for all mortars, regardless of the moisture states of sand. As a typical example, flexural strength of SSD-CR0 at 1-day, 3-day, and 7-day ages was lower than that at 28-day age, 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. [28], Hari and Sudan [29] and Luhar et al. [30]. This could be attributed to the formation of cement hydration products over time [8].

However, the replacement of NS by RS led to the reduction in flexural strength of mortar, regardless of the moisture states of sand. Based on the results at 28-day age, the flexural strength of the CR50 specimen was lower by 7.4–13.8% when compared to that of the CR0 specimen. This trend was similar to the study conducted by Ghania et al. [22]. The substitution of fine and porous of RS was responsible for the decrease in flexural strength [31].

Additionally, there was worth noting that the flexural strength of the mortar specimen with sand in the SSD state was significantly improved by 23.3–32.4% when compared to that with sand in the DS state, regardless of sand types and replacements (see Figure 4). These results tended to be similar to studies of Montoya et al. [12] and Tong [14] regarding the use of recycled aggregates in SSD and DS states for concrete casting. According to Lee and Lee [32], the improvement was attributed to the effectiveness of internal curing provided by the SSD aggregates.

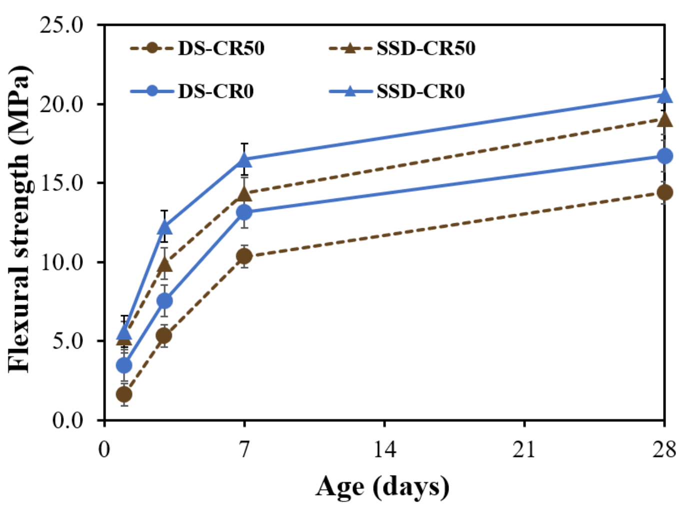

Figure 4. Influence of moisture states of sand on flexural strength of hardened mortar.

3.3. Compressive strength of hardened mortar

Figure 5 presents the compressive strength of the mortars containing sands at SSD and DS states at 1-day, 3-day, 7-day, and 28-day ages. Similar to the flexural strength of the cement-based mortar (mentioned at section 3.2), the compressive strength showed a similar trend of increasing over time, regardless of moisture states of sand. For example, compressive strength of DS-CR0 at 1-day, 3-day, and 7-day ages was lower than that at 28-day age, and the same trend was observed for the remaining specimens. The results in the development of compression strength were similar to the research conducted by Krishna and Kumar [33], and Montoya et al. [12]. This confirmed again the formation of cement hydration products over time [8].

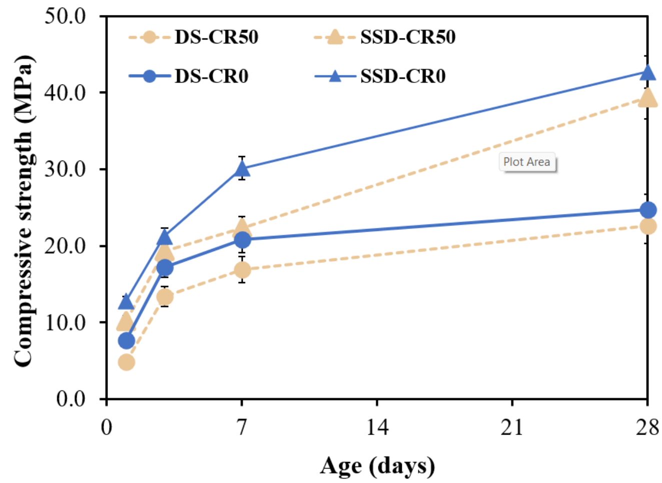

Figure 5. Influence of moisture states of sand on compressive strength of hardened mortar.

However, at the same moisture state of sand, there were gradual reductions in compressive strength as RS replacement increased at any age. As compared to CR0 at 28 ages, compressive strength of CR50 was lower by 7.8–8.9%. Similar findings have been reported by Mushtaq et al. [2] and Gholampour et al. [34] wherein compressive strength was significantly decreased as WFS substitution increased. As the findings by Parasha et al. [31] and Siddique and Noumowe [35], the decrease in compressive strength could be attributed to a combination of two factors including (1) the compaction of the mixture; (2) the excess fine materials in the mortar, which had the potensstial to settle on the surface of the aggregates, and prevented the formation of bonds between these aggregates and the cement paste.

According to Figure 5, the compressive strength of mortar using sand at SSD state significantly enhanced by 72.2–74.3% when compared to that with sand in the DS state, regardless of sand types and replacements. For instance, the SSD-CR0 specimen exhibited a higher compressive strength compared to the DS-CR0 specimen. A related trend was observed for the compressive strength of CR50, which trended similar to the study conducted by Tong et al. [36]. According to Al-Khaiat and Haque [37], this variation was attributed to the water stored in SSD sand particles, which kept the cement hydration process going.

3.4. Relationship between flexural and compressive strengths of hardened mortar

A correlation between the flexural and compressive strengths of the cement-based mortar is shown in Figure 6. The results of strength from mortars using sand at different moisture states indicate a general upward trend, suggesting that as the compressive strength increases, the flexural strength also tends to increase. Furthermore, the data showed a strong linear relationship with the correlation coefficient $R^2 = 0.9002$. Based on the chart as shown in Figure 6, the flexural strength of the cement-based mortar was possible to make inferences from the compressive strength.

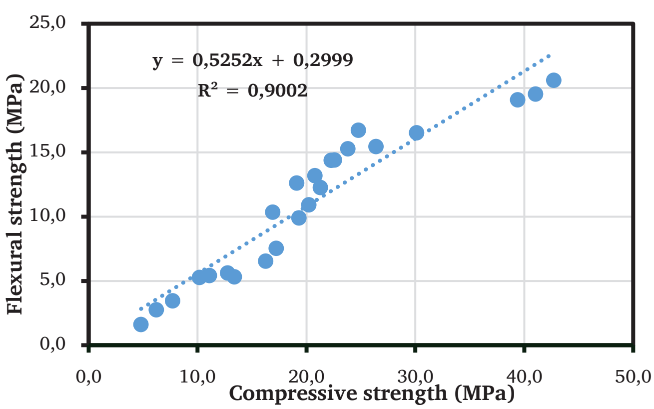

Figure 6. Relationship between flexural and compressive strengths of cement-based mortar.

4. Conclusions

This study employs the influence of moisture states of RS from construction sites as the replacement of NS on the consistency, compressive strength, and flexural strength of hardened mortar. From the results obtained in this study, the following statements can be summarized:

- The consistency of fresh mortar, compressive and flexural strengths of hardened cement-based mortar decreased corresponding to the increase in the use of RS, regardless of the moisture states of sand.
- Regardless of the types of sand, the SSD state of sand could enhance the consistency of fresh mortar and mechanical strengths of the hardened mortar.

Consequently, the experimental results in the present study showed the possibilities of the application of RS from construction sites in cement-based mortar production.

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