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Utilizing Recycled Sand from Excavation Wastes for Sustainable Cement Mortar Production

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Abstract

This research investigates the feasibility of using recycled sand produced from excavation waste as natural sand alternative for sustainable cement mortar production. Two different types of recycled sand, namely limestone powder (RS1) and scalping powder (RS2), were collected and characterized. Thorough characterization encompassed particle size distribution, morphology, specific gravity, water absorption, and chemical composition. The recycled sands are then utilized to replace natural sand in mortar compositions, with varying proportions reaching up to 20%. The properties of the produced mortars were examined using the following tests: compressive strength, workability, density, water absorption, and thermal stability via thermogravimetric analysis (TGA). The results revealed that the inclusion of RS in cement mortar led to a decrease in compressive strength and workability, coupled with an increase in water absorption for both types of recycled sand. The decline in strength became more pronounced with higher RS proportions, with RS1 demonstrating superior compressive strength compared to RS2. Despite these effects, the thermal stability of cement mortar was only marginally impacted by the presence of RS. This research underscored the promise of recycled sand from excavation waste in cement mortar production, highlighting performance characteristics and suggesting further investigation, especially regarding thermal behavior under elevated temperatures.

Keywords: Recycled Sand; Excavation Waste; Sustainable Mortar; Strength; Water Absorption.

1. Introduction

The construction industry has become a significant consumer of natural resources such as natural sand and a major contributor to environmental degradation, habitat destruction, riverbank erosion, and ecological disruption [1]. In response to these concerns, researchers are exploring various options as substitutes for natural sand in the construction industry. The aim is to develop alternative materials that possess similar physical properties and performance to natural sand while mitigating environmental impacts and ensuring the sustainability of resources. One of the suggested alternatives in the literature is recycled sand from excavation waste [2–4]. Excavation wastes (EW) as part of Construction Wastes (CW) have significant environmental and economic challenges globally, as they account for a substantial portion of the waste generated worldwide [5]. The improper handling and disposal of EW can have adverse effects on the environment, including land and water pollution, depletion of natural resources, and increased greenhouse gas emissions [6]. In this regard, incorporating recycled sand from excavation waste into concrete production can not only decrease the demand for natural sand but also mitigate the volume of waste sent to landfills, thereby minimizing their environmental impact.

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In contrast to the extensive research conducted on coarse recycled aggregates [7–9], there have been a limited number of studies over the past decades exploring the potential use of recycled fine aggregate (FA) or recycled sand from excavation wastes in concrete production. Several researchers have noted that incorporating recycled fine aggregate from excavation waste could potentially negatively affect the properties of cement mortar due to several factors, such as high water absorption, low specific gravity, and decreased bulk density [2, 10–16]. However, other studies have reported improvements in the mechanical strengths of cement mortar when natural sand is replaced by recycled sand from excavation wastes [3, 17–19].

In a study conducted by Mundra et al. [18], replacing natural sand with a fine aggregate derived from sandstone excavation waste in mortar led to improvements in its mechanical properties. This enhancement can be attributed to the filler effect of sandstone excavation waste particles and the formation of a dense concrete matrix with up to 30% replacement. Similar results were found by Ma et al. [20], who noted that the limestone sand revealed a slightly higher compressive strength than the natural sand. On the other hand, some researchers found that using recycled excavation waste as sand replacement decreased the mechanical properties. For instance, Safiddine et al. [21], who studied the influence of limestone crushed sand on the rheological properties of cement mortar, concluded that the mortar based on limestone crushed sand has a low loss of rheological properties compared with a mortar based on siliceous sand. Similar results were found in another study where the incorporation of 15% limestone fines in concrete caused a reduction in compressive strength regardless of the cement type [16].

Priyadharshini et al. [2] reported that the compressive strength of mortar decreases with increasing the content of untreated excavated soil. This reduction was attributed to the loosening effect of clay particles between cement and aggregate. The presence of clay or fines increases the surface area that needs to be covered by cement paste, leading to weak links in the network when there is insufficient cement paste. Consequently, mortar with raw excavation soil exhibited strength reductions of 55% and 78%, compared to the control mortar.

The predominant focus within the realm of recycled aggregate (RA) has overwhelmingly leaned towards the utilization of coarse RA, leaving the application of RA fines relatively unexplored. This skewed emphasis has resulted in a constrained utilization of recycled sand (RS), primarily due to the inadequacy of comprehensive scientific research in this specific domain. Recognizing and aiming to bridge this critical gap, the present research delves into an in-depth exploration of the feasibility associated with integrating recycled sand (RS) derived from excavation wastes into the production of cement mortar. In this comprehensive investigation, various aspects, such as the physical and mechanical properties of recycled sand, its potential impact on the structural integrity of cement mortar, and its overall viability as a sustainable construction material, will be meticulously examined. The study endeavors to significantly contribute to the existing body of knowledge in this area, providing valuable insights that could pave the way for a more extensive and efficient utilization of recycled sand in construction practices. By addressing the current limitations and shedding light on the untapped potential of RS, this research seeks to promote sustainable practices and further the understanding of how recycled materials can be optimally harnessed in the construction industry.

1.1. Production Process of Recycled Sand from Excavation Wastes

Substantial amounts of excavation waste (EW) are abundant in Qatar due to extensive infrastructure development over the past two decades. A significant portion of this material has been transported to Rawdat Rashid landfill sites for processing and recycling. The processing of EW involves a series of steps such as mechanical, manual, and magnet separation of foreign, metal, and lightweight materials, followed by crushing and screening to produce various sizes. This process is executed through three production lines: jaw crusher and screening, impact crusher and screening, and secondary impact and screening, as depicted in Figure 1. The result is recycled products suitable for diverse applications. Under the current production procedures, two primary types of recycled aggregate are generated: coarse recycled aggregate (RA) with dimensions ranging from 5-10 mm and 10-20 mm, and fine recycled sand (RS) measuring 0-5 mm.

Figure 1. Production lines of recycled aggregate from excavation waste [22]

In this research, two different types of recycled sand, namely limestone powder (RS1) and scalping powder (RS2), were characterized and subsequently utilized to replace natural sand in mortar compositions, with varying proportions reaching up to 20%. The study comprehensively examines the physical, fresh, and harden properties, and the thermal stability of mortars containing different percentages of RS.

2. Experimental Program

2.1. Recycled Sand Characterization

Two types of recycled sand, Figure 2, extracted from excavation wastes were used in this study, limestone sand (RS1) and scalping powder sand (RS2). The recycled sands were received from Qatar Primary Materials Company (Al-Awalia). A comprehensive characterization was conducted on these recycled sands along with natural sand (NS) encompassing various aspects including particle size distribution (PSD), particle morphology, specific gravity, water absorption, and chemical composition. The sieve analysis test for all sands was performed as per ASTM-C136 [23]. The PSD curves are presented in Figure 3. The median particle sizes (D50) for RS1, RS2, and NS were determined as 1.18 mm, 600 µm, and 300 µm, respectively. In addition, the fineness modulus of NS, RS1, and RS2 was calculated as 4.5, 4.7, and 4, respectively, using Equation 1:

$$F.M = \frac{\text{cumulative \% retained}}{100} \tag{1}$$

Figure 2. Natural and recycled sand used in this study

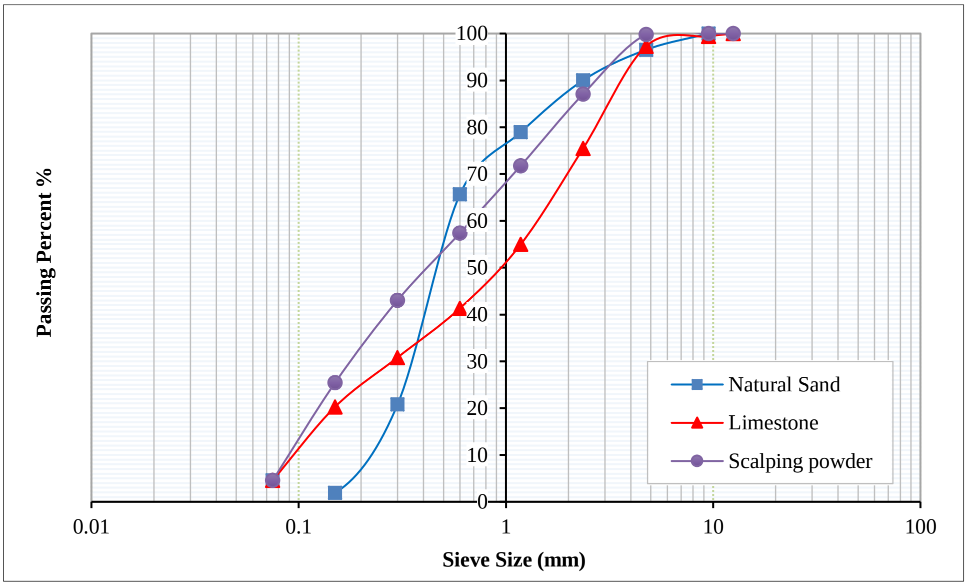


Figure 3. Particle size distribution of sands

The results indicated that recycled sands contain a higher proportion of fine particles in comparison to natural sand. The morphology of sand particles was examined using Scanning Electron Microscopy (SEM) with the NOVA NanoSEM 450 instrument. Figure 4 reveals the irregular and non-spherical shapes of both RS1 and RS2 particles. The irregular and non-spherical shapes of recycled sand can be attributed to various factors related to the nature of the original source material (excavation waste) and the recycling process itself, especially the crushing and screening process.

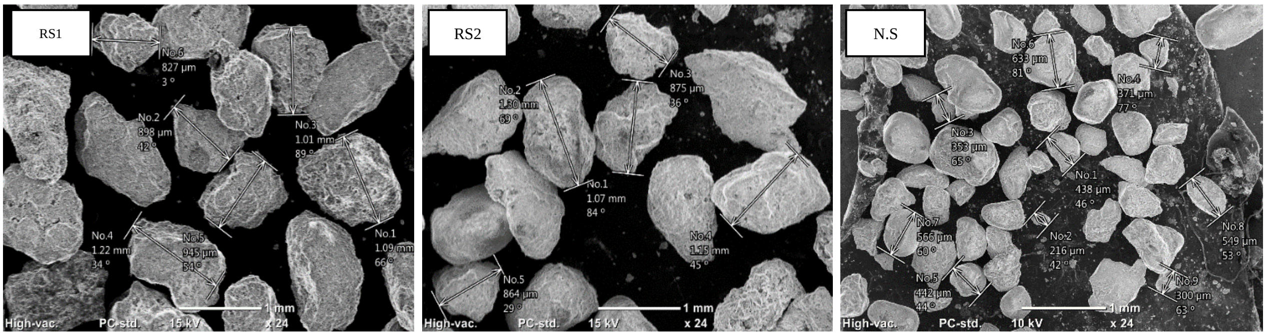


Figure 4. SEM imaging of RS1, RS2 and NS

To ascertain the chemical composition of the recycled sands, X-ray fluorescence (XRF) analysis was conducted using the JSX 3201M (Jeol) spectroscopy apparatus. The XRF analysis (Table 1) reveals notable differences in the chemical composition of the three sands. RS1 and RS2, being recycled sands, have a considerably higher content of calcium oxide (CaO) compared to NS, while NS has a higher silicon dioxide (SiO_2) content, typical for natural sands. The differences in chemical composition between recycled sands and natural sands are primarily due to the origin and processing methods. Recycled sands are typically produced by crushing and processing construction excavation waste materials. These waste materials can contain various contaminants and impurities, including concrete debris, cement, and other construction-related materials that often contain calcium-based compounds like calcium carbonate ($CaCO_3$). During the recycling process, these contaminants may not be fully removed, leading to a higher CaO content in recycled sands. On the other hand, natural sand is formed through natural geological processes. It primarily consists of quartz grains, which are composed mainly of silicon dioxide (SiO_2). Since natural sands are not subjected to the same types of contaminants as recycled materials, they tend to have a higher SiO_2 content.

Table 1. Chemical composition (XRF) of sands

Oxides	NS (%)	RS1 (%)	RS2 (%)
CaO	20.1	73.0	70.1
SiO_2	61.7	15.1	15.6
Fe_2O_3	1.6	2.2	2.1
SO_3	5.3	1.8	3.8
Sc_2O_3	0.2	0.5	0.5
K_2O	1.5	0.3	0.3
SrO	0.1	0.1	0.2
TiO_2	0.2	0.1	0.1
Mgo	3.8	6.5	6.3
ClO_2	0.3	0.2	0.3
MnO	0.1	0.1	0.1
Al_2O_3	5.0	-	0.4

The specific gravity and water absorption of the sands have also been determined in this study in accordance with the ASTM-C127-15 [24] standards, respectively. The results presented in Table 2 show the specific gravity yielded values of 2.72, 2.75, and 2.65 for RS1, RS2, and NS, respectively. NS showed the lowest specific gravity and the lowest proportion of water absorption among all the other samples. Recycled sand possesses around 450% higher water absorption values than natural sand. Recycled sands often have higher water absorption compared to natural sand due to several factors related to their composition and processing [26, 26]. Recycled sands are typically derived from construction waste materials, which can include a wide range of materials such as concrete, mortar, bricks, and aggregates. These materials may contain porous components, like crushed concrete or masonry fragments. These porous components can readily absorb water, leading to higher overall water absorption in recycled sands [27]. In addition, the shape and surface characteristics of particles in recycled sands can be different from those in natural sand. Irregular or rough surfaces can increase the surface area available for water absorption, leading to higher water absorption rates [26]. Moreover, recycled sands may contain residues of binders and cementitious materials used in the original construction materials. These residues can have the ability to absorb and retain water [1].

Table 2. Specific gravity and water absorption

Sample	Water absorption (%)	SG
NS	1.87	2.65
RS1	10.79	2.72
RS2	9.96	2.75

2.2. Materials and Mortar Specimens' Preparation

Control mortar samples were prepared using a mixture of sand, cement, and water. The sand was locally available; silica sand possessed a fines modulus of 4.0, a specific gravity of 2.65, and exhibited a water absorption rate of 1.87%. This sand was in compliance with the ASTM C778 standard [28]. Type I Portland cement, "CEM I-42.5 R," in accordance with BS EN 197 standards, was selected for use. As mentioned in the previous section, two types of recycled sand were used: RS1 and RS2. The recycled sands were employed as substitutes for natural sand in mortar production at four replacement levels: 5%, 10%, 15%, and 20% by weight of the sand component. A total of seven distinct mortar mixes were prepared, as outlined in Table 3. This encompassed one control mix devoid of recycled sand, four mixes utilizing RS1, and an additional four mixes integrating RS2. Following ASTM C305 standards [29], the cube specimens were prepared. Initially, a combination of silica sand and recycled sand, following predetermined substitution percentages, was introduced into the mixer. Then, cement and water were added to the mix and mixed for three minutes. After this, the flowability of the resulting mortar was evaluated using a flow table test. The formulated mortar was then used to create cube specimens measuring 5 × 5 × 5 cm for subsequent compressive strength testing. Curing periods of 1, 7, and 28 days in a water environment were applied before conducting the compression strength tests.

Table 3. Mix Design

Mix #	Specimen designation	Cement (kg/m^3)	Natural Sand (kg/m^3)	RS2 (kg/m^3)	RS1 (kg/m^3)	Water (kg/m^3)
1	Control	500	1375	0	0	300
2	RS1 5%	500	1306.25	0	68.75	300
3	RS1 10%	500	1237.5	0	137.5	300
4	RS1 15%	500	1168.75	0	206.25	300
5	RS1 20%	500	1100	0	275	300
5	RS2 5%	500	1306.25	68.75	0	300
6	RS2 10%	500	1237.5	137.5	0	300
7	RS2 15%	500	1168.75	206.25	0	300
8	RS2 20%	500	1100	275	0	300

2.3. Test Procedures

2.3.1. Compressive Strength

The investigation into the mechanical properties of cementitious binders containing RS was conducted via compressive strength assessment in accordance with the ASTM C109 standard [30]. The specimens were subjected to loading until failure, employing a loading rate of 1.4 kN/s. The average strength values, based on three specimens tested for each mixture, were subsequently documented. The samples entailed the utilization of the prefixes "RS1" and "RS2," followed by a number, which refers to the replacement ratio.

2.3.2. Workability

The assessment of the workability of the cementitious binder containing RS was conducted through the utilization of the flow table test, following the guidelines of ASTM C1437 [31]. Subsequently, the mean value derived from four individual measurements for each blend was computed and subsequently documented.

2.3.3. Density

The study examined how RS affects the density of mortar. Three mortar cubes, each measuring 50 mm, were prepared for every mix design and allowed to cure for a period of 28 days in water. Subsequently, these mortar cubes were subjected to an oven environment for 24 hours, maintaining a temperature of 110°C. Afterward, the mortar specimens were extracted from the oven and allowed to cool at room temperature for a duration of 2 hours, during which their dry weights were documented. The oven-dry density was then computed by dividing the oven-dry weight by the volume of each specimen, and the resulting values were averaged based on the three mortar cubes used in the analysis.

2.3.4. Water Absorption

The water absorption of cement mortar specimens was determined in accordance with the ASTM C1403 standard [32]. For each mix design, three 50 mm mortar cubes were subjected to a temperature of 110°C in an oven for a duration of 24 hours at the age of 28 days. The mortar specimens were taken out from the oven and allowed to cool at room temperature for a duration of 2 hours. The dry weight of all specimens was measured, following which the mortar specimens were subsequently put into a container. The specimens were immersed in water at a depth of 3 ± 0.5 mm. The weight of the mortar specimens was measured at time intervals of 0.25 hours, 1 hour, 4 hours, and 24 hours. Subsequently, the weight measurements were conducted on a daily basis until the point at which no apparent change in weight was seen between consecutive weighing.

2.3.5. Thermogravimetric Analysis (TGA)

The research methodology involved investigating the impact of recycled sand on the thermal stability of cement mortar under elevated temperatures through thermogravimetric analysis (TGA). Fragments extracted from designated specimens were initially ground to a size of 45 mm and subsequently analyzed using the Thermogravimetric Analyzer TGA 4000 PerkinElmer device within the temperature range of 25°C to 550°C. Figure 5 shows the research methodologies for the experiments conducted in this research.

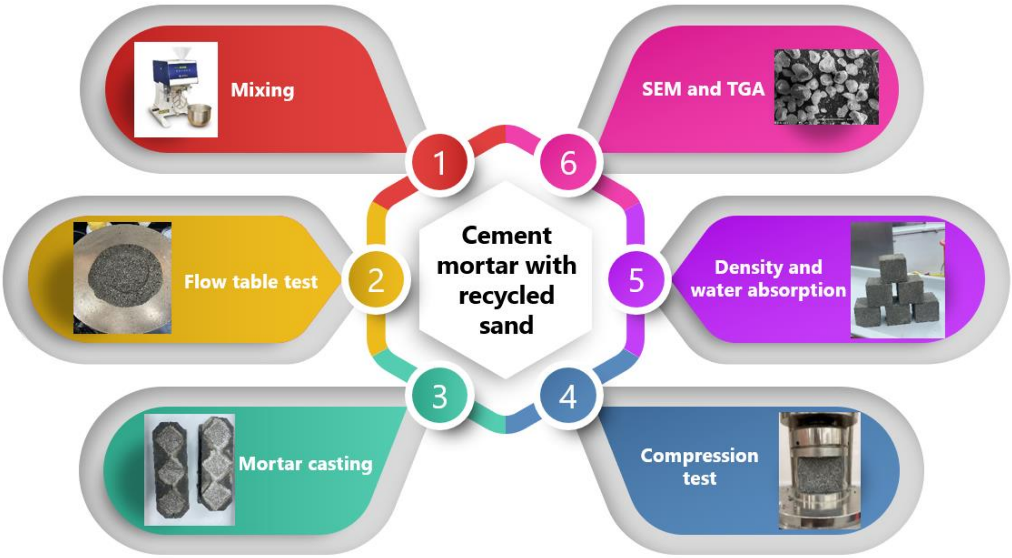


Figure 5. Research methodologies and tests

3. Results and Analysis

3.1. Workability

Figure 6 presents the results of the flow table test for mortar, shedding light on the impact of replacing a portion of the sand content with recycled sands (RS1 and RS2) on the workability of the mortar. The findings reveal significant insights: when 5% of the sand content was replaced with RS1, there was a noticeable 16% reduction in the mortar's workability. This reduction became more pronounced as the replacement ratio increased, with workability decreasing by 32% and 52% for 10% and 15% replacements, respectively. For RS2, the replacement of natural sand with 5%, 10%, and 20% recycled sand led to substantial decreases in mortar workability by 10.5%, 36.8%, and 52.6%, respectively. Figure 7 illustrates a critical point, which is that the workability of mortar with a 20% replacement of recycled sand failed. This observation can be attributed to several factors: the high-water absorption capacity of recycled sand, as noted in the previous section can lead to reduced mortar workability [16, 19]. The absorbed water may not be available for lubrication and flow, making the mortar less workable. In addition, the uneven and rough surface of recycled sand, as discussed in studies such as Cortes et al. [26], can contribute to decreased workability. Irregular particles and rough surfaces can hinder the flow of mortar and increase friction, making it less malleable. These findings align with prior investigations. For instance, Hu and Wang [33] previously demonstrated that the use of limestone sand with inadequate particle shape can result in reduced flowability of mortar compared to river sand. Moreover, research has shown that when substituting natural sand with crushed sand, a higher quantity of paste is often required to achieve satisfactory working performance. This is attributed to the more angular shape of crushed sand compared to the nearly spherical shape of natural sand [26]. In summary, the flow table test results highlight the crucial influence of replacing natural sand with recycled sand on mortar workability. It underscores the importance of carefully selecting the type and percentage of recycled sand to maintain desired workability levels in construction applications. Additionally, the findings align with existing research that emphasizes the significance of particle shape and surface characteristics in determining the flowability and workability of construction materials.

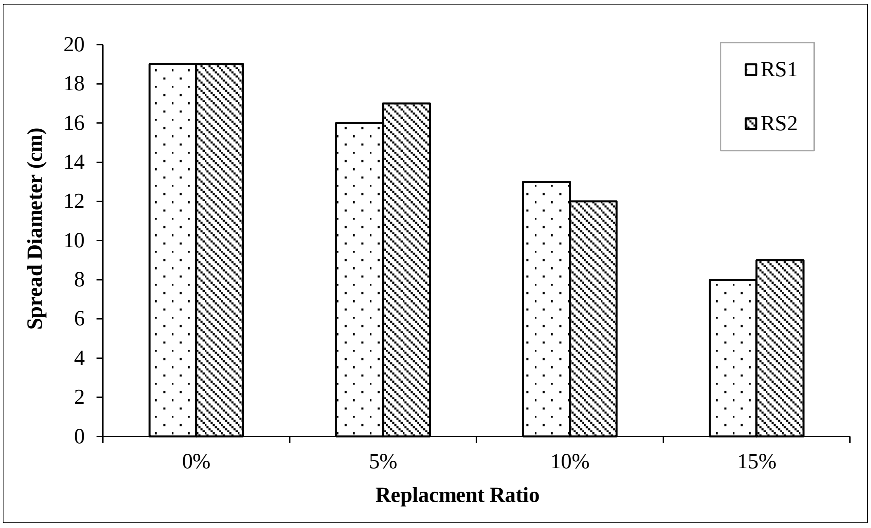


Figure 6. Flow table results of mortars with RS

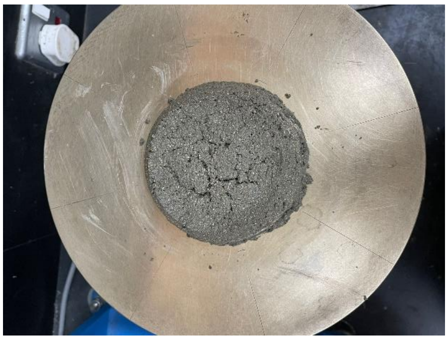


Figure 7. 20% RSA sample with very low flowability

3.2. Compressive Strength

The impact of replacing natural sand with recycled sand on the compressive strength of cement mortar at three different curing periods was investigated. The results are summarized in Table 4 and Figure 8.

Table 4. Compressive strength results

	1 Day		7 days		28 days	
Specimen	**Strength (MPa)**	**Enh. %**	**Strength (MPa)**	**Enh. %**	**Strength (MPa)**	**Enh.%**
NS	5.4		15.1		27.2	
RS1- 5%	6	13	13.3	-12	24.87	-9
RS1 -10%	9.1	68	13.7	-10	24.6	-10
RS1 -15%	8.3	53	12.8	-16	21.8	-20
RS2- 5%	5.7	5	13.5	-10	23.3	-14
RS2- 10%	8.1	50	12.9	-15	22.8	-16
RS2-15%	7.5	39	12	-19	19.3	-29

It is clear from the results that the early-age (1-day) compressive strength of the mortar generally improved for all replacement ratios, especially with 10% replacement of both RS1 and RS2. However, these enhancements were not sustained at later ages (7 days and 28 days). The 7-day and 28-day compressive strengths were lower for most replacement scenarios compared to the reference samples, indicating that the long-term strength of the mortar is compromised when a significant portion of NS is replaced with recycled sand. The results for RS2 generally showed a more pronounced reduction in compressive strength compared to RS1, particularly at higher replacement percentages and at later curing periods. The decrease in strength at later ages could be attributed to various factors, including differences in water absorption characteristics, particle size distribution, and mineral composition between natural sand and recycled sands [34].

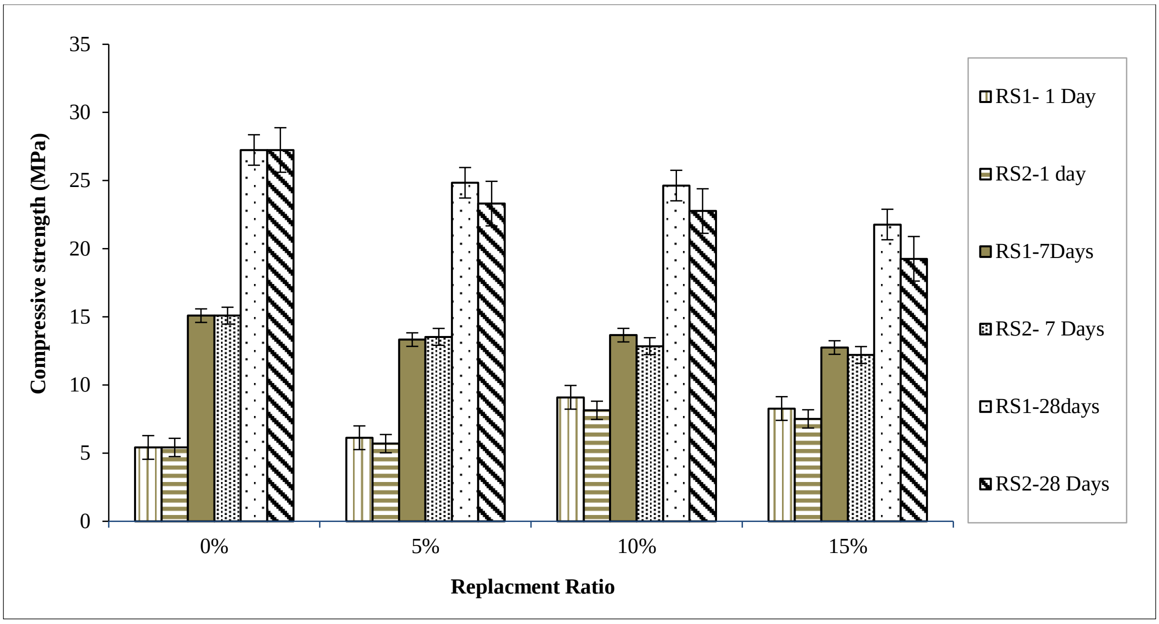
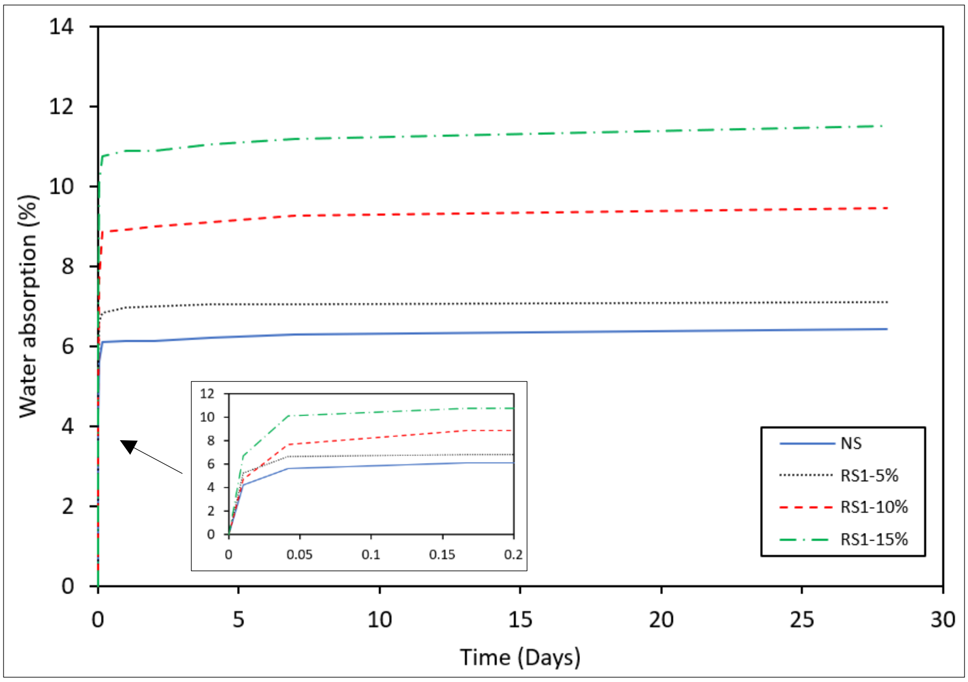


Figure 8. Compressive strength development of cement mortar with recycled sand

Similarly, Almeida et al. [35] noted that replacing 5% of sand with recycled crushed stone led to increased concrete strength after 7 days. They attributed this strength improvement to improved hydration and enhanced bonding between concrete components. However, at higher replacement levels, a decrease in compressive strength was observed. Further investigation and optimization of the mix design, potentially incorporating additional additives or treatments to mitigate the negative effects on strength, may be necessary when using recycled sands in concrete applications.

3.3. Water Absorption

Figure 9 shows a graph of the water absorption of cement mortar with various amounts of RS in place of natural sand. It is clear that adding RS to the mortar increased water absorption. Regardless of the precise kind, this absorption capacity increased as the ratio of RS increased. However, samples with RS1 showed higher water absorption than those with RS2, that can be explained by the higher water absorption of RS1 as showed in Table 2. In addition, it was noted that all mortar specimens needed almost one day to reach the plateau stage with constant absorption. Similar behavior was reported in previous studies [36].



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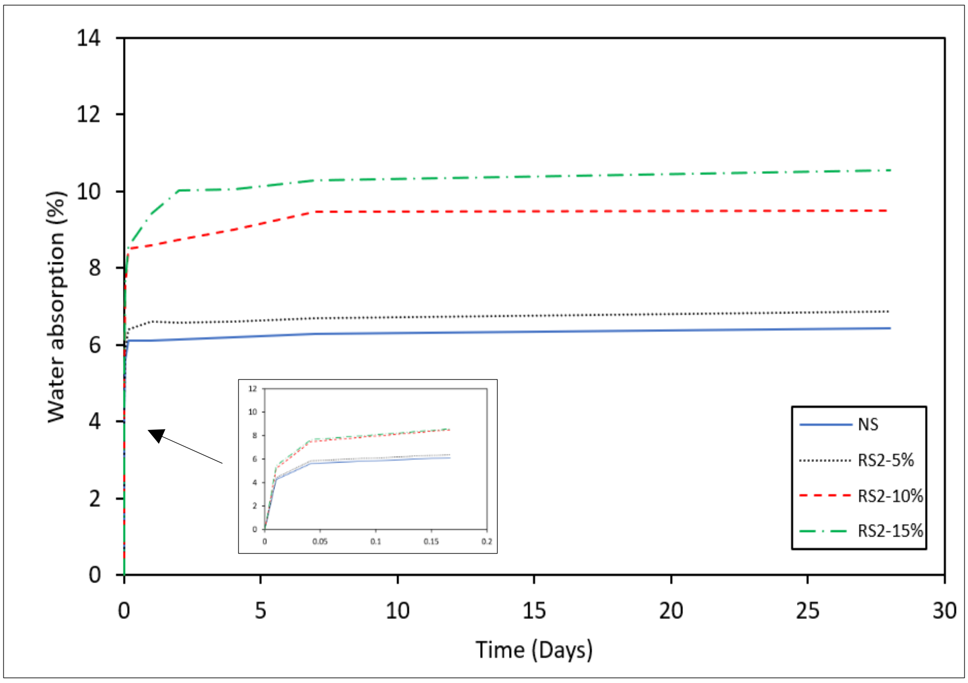


(b)

Figure 9. Water absorption of mortar with recycled sand

3.4. Density

Figure 10 illustrates the density variations in mortar as a result of different replacement ratios of recycled sand in place of natural sand. The figure provides empirical evidence that substituting natural sand with RS leads to a modest but consistent increase in mortar density. This increase becomes more significant as the replacement ratio escalates, largely owing to the higher specific gravity of recycled sand. On average, this increase amounts to approximately 7%. Understanding these density variations is crucial when making decisions about the composition of mortar mixes in construction applications.

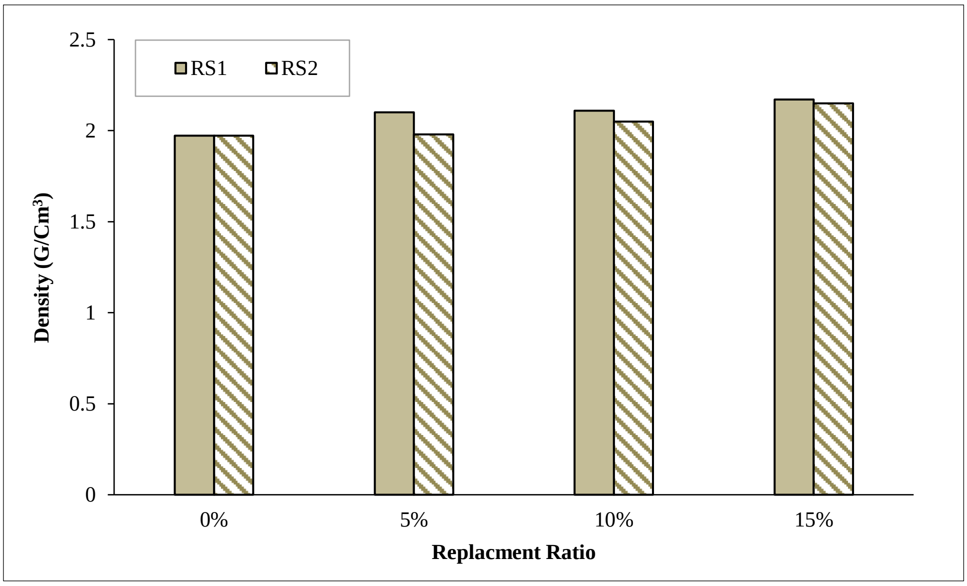
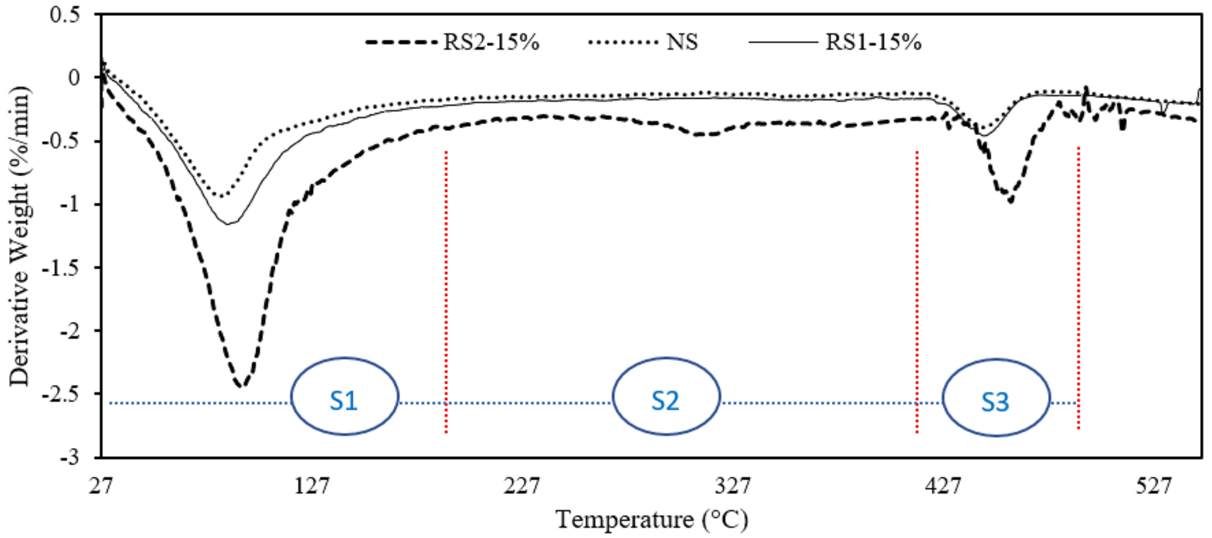


Figure 10. Density of cement mortar with RS

3.5. Thermogravimetric Analysis

Figure 11 illustrates the TGA curves and corresponding derivative function (DTG) curves for cement mortar incorporating 15% recycled sand. The control cement mortar specimen exhibited a total weight loss of nearly 7% when heated at 550°C, consistent with existing literature [37, 38]. Substituting 15% of natural sand with recycled sands RS1 and RS2 resulted in increases in weight loss of 8.5% and 18%, respectively. The thermogravimetric profiles in Figure 11-a revealed three distinct phases, corresponding to three main weight loss stages. The initial weight loss occurred between 30°C and 200°C, attributed to unbound water vaporization. Subsequently, a stable weight loss rate was observed between 200°C and 400°C (S2). The third weight loss phase, between 400°C and 475°C, was linked to the decomposition of calcium hydroxide ($Ca(OH)_2$), in line with findings in the literature [39]. In Figure 11-b, it is evident that the first peak in the DTG curves of cement mortar with recycled sand was higher and wider compared to the control sample, indicating a larger amount of hydrates [40]. The second peak in the DTG curves of cement mortar with RS2 was notably higher than that of the control specimen, accompanied by a rightward shift. This observation suggests a reduction in the hydration of ordinary Portland cement (OPC) in the presence of RS2, possibly due to decreased consumption of Ca $(OH)_2$ [41] or influenced by the moisture content of RS. These findings indicate that substituting natural sand with recycled sand (RS1) may not impact thermal stability, but the use of RS2 could have adverse effects. It is advisable to conduct a comprehensive examination of the performance of cement mortar containing RS under elevated temperatures in future research.



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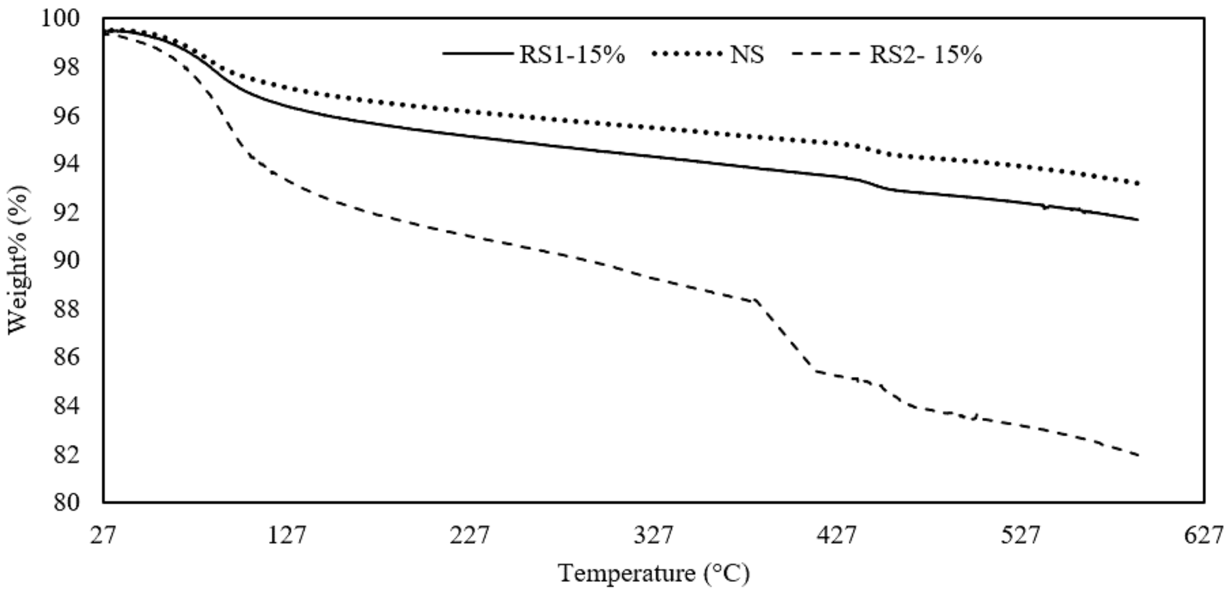

(b)

Figure 11. (a) TGA profiles (b) DTG profiles for cement mortar with RS

4. Conclusions

The feasibility of utilizing recycled sand derived from excavation wastes in cement mortar production is explored in this case study. Two types of recycled sand, limestone powder (RS1) and scalping powder (RS2), were received, characterized, and used with various replacement ratios to replace natural sand in cement mortar production. The fresh and hardened properties of the mortar were investigated. The following conclusions could be drawn:

- Replacing natural sand with recycled sand caused a reduction in the compressive strength and the workability of the mortar, regardless of the type of recycled sand. The reduction was more pronounced in the case of using RS2.

- Without using superplasticizers, 15% of the natural sand content in the mortar mix could be replaced by recycled sand produced from excavation waste. Exceeding this ratio would cause a severe reduction in the flowability of the mortar.
- Substituting natural sand with RS led to an insignificant increase in the mortar density.
- Replacing natural sand with recycled sand caused an increase in mortar water absorption. Regardless of the type of RS, the absorption capacity increased as the ratio of RS increased.
- Substituting natural sand with recycled sand (RS1) may not impact thermal stability, but the use of RS2 could have adverse effects. It is advisable to conduct a comprehensive examination of the performance of cement mortar containing RS under elevated temperatures in future research.

5. Declarations

5.1. Author Contributions

Conceptualization, M.R.I.; methodology, N.B.; validation, M.R.I. and O.M.; formal analysis, M.R.I. and N.B.; writing—review and editing, M.R.I. and N.B.; visualization, N.B.; supervision, M.R.I.; project administration, N.B.; funding acquisition, M.R.I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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