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Research Article

A comparative study on the use of waste brick and glass in cement mortars and their effects on strength properties

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ABSTRACT

Sustainable development of the construction industry should use recycled materials to the greatest extent to reduce natural hazards due to the increased accumulation of waste and the depletion of natural resources. However, engineering applications using waste materials are always expected to perform satisfactorily. In this aspect, detailed and systematically carried out experimental studies are critical in selecting the type and the quantities of waste materials that will be recycled through their use within engineering applications. This study provides systematically produced experimental data on compressive and flexural strength performance to quantitatively compare the effects of using different percentages of waste glass and brick aggregates in cement mortars with a specified workability characteristic. Results show that mortar samples with waste glass aggregates perform better under compressive loading since only around 14% strength decrease compared to the control mix was yielded with the inclusion of waste glass. In contrast, in both cases, a 30% strength decrease was recorded with the inclusion of waste bricks for 100% replacement of natural sand in the mortars. In the case of flexural strength performance, 50% replacements of natural aggregates with waste bricks and glass yielded around 27% and 38% strength decrease, indicating that using waste brick in cement mortars could result in a better flexural strength performance in comparison, provided that its content is controlled. Replacement of natural sand in cement mortars with waste brick and glass yielded less significant flexural strength, decreasing the difference between the two types of wastes when the replacement ratio was as high as 100%. Hence, based on the presented experimental evidence, it is concluded that the decision on the type and the quantity of the waste materials to be used should be made considering the area of the use of the mortar and its expected service type.

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1. INTRODUCTION

Concrete is undoubtedly one of the most popular construction materials used all around the globe. The fact that 75% of the volume of concrete is composed of aggregates brings two important issues. Firstly, and in the civil engineering aspect, the quality and performance of concrete constructions would be highly affected by the characteristics of the aggregates used within, considering the volume they occupy in the mix [1]. Secondly, and globally, using

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natural (i.e., quarried) aggregates for manufacturing billions of tons of concrete would accelerate the depletion of natural sources of aggregates on planet Earth while posing threats to nature in most cases. Several aggregate quarries on the Beşparmak (Pentadaktylos) Mountains in North Cyprus that are unfortunately mismanaged are observed to cause loss of sources loss of vegetational and animal life in their surroundings, as seen in Figure 1. Another environmental hazard that has been building up simultaneously is the increased quantities of waste generation caused by the needs of modern life when societies do not adopt the concept of sustainability. Engineers and scientists have proposed using waste materials as a replacement for natural aggregates in concrete in the last decades to reduce the two aforementioned environmental hazards, and the published works in the literature yielded promising results for this approach [2–6]. Similar to concrete, cement mortars are also consumed in constructions in huge quantities, mainly for all kinds of repair and maintenance works as well as in masonry works and so forth [7]. Additionally, since the main difference between mortar and concrete is the size of the aggregates used within them, cement mortars are also widely used in civil engineering research studies due to being accepted as highly indicative of concrete's performance and behavior. Hence, the use of waste materials to replace fine aggregates in cement mortars is also of concern.

Regarding the use of waste materials as a replacement for natural (i.e., quarried) fine aggregates in cement mortars, several interesting previous works have been considered. Among these, Bektas et al. [8] propose using crushed waste brick as a replacement for natural sand in mortars and report that the highly porous nature of brick aggregates affects the properties of fabricated mortar bars. This property of brick aggregates has been reported to yield increased water absorption for the mortars. Another noteworthy observation reported by this study was that the compressive strength of the mortars containing waste bricks was not negatively affected up to a limit of 20% (by mass) replacement of natural aggregates [8]. Zhu and Zhu (2020) [9] also report that the porous nature of waste brick aggregates caused increased water absorption and reduced compressive strength of cement mortar samples when added beyond specific contents. However, the surface texture of these waste aggregates has been reported to yield higher splitting tensile strength [9].

Another interesting study was presented by Tan and Du [10], which proposes using crushed waste glass as a replacement for natural sand in cement mortars. This interesting study reports that waste glass aggregates have smooth surface texture, and this characteristic yields weaker bonds between the waste aggregate and the cement paste, eventually yielding a decrease in the tensile strength of the mortar samples. Lu and Poon [11] also reports similar finding on the use of waste glass as a replacement for natural sand in cement mortars, stating that increased contents of glass aggregates yielded decreased tensile strength of mortars due to the smooth texture of this type of waste aggregates. Another noteworthy performance information provided by this study indicates that glass aggregates have very low absorption characteristics. Hence, they do not negatively affect the workability of fresh cement mortar mixes [11].

Figure 1. A view of the damaged nature due to aggregate quarries on Beşparmak (Pentadaktylos) Mountains, North Cyprus.

Table 1. The mortar mixes used and their waste types and contents

Mix name	Natural aggregate (NA)	Recycled brick aggregate (RBA)	Recycled glass aggregate (RGA)
Mix 1 (control set)	100%	0	0
Mix 2a	50%	50%	0
Mix 2b	0	100%	0
Mix 3a	50%	0	50%
Mix 3b	0	0	100%

These noteworthy and interesting research studies provide insights into some characteristics of mortar bars produced using mentioned waste aggregates. However, each study is observed to have an independent experimental campaign design, and hence, it becomes difficult to relate and compare their findings for engineering applications. Therefore, the related literature has detected *a lack of systematical and comparable experimental information* on cement mortars' fresh and hardened properties specifically made with waste glass and bricks. Therefore, the main objective of this study is to provide experimental data to investigate the performance of cement mortars having specified workability characteristics that are produced with recycled glass aggregates (RGA) and recycled brick aggregates (RBA) that were used as replacements for natural (i.e., quarried) sand. In this way, the suitability and the advantages of using waste glass and waste bricks in cement mortars could be directly compared based on the obtained experimental results, yielding potentially beneficial insights for practical applications in the construction sector aiming to contribute to the sustainable development of societies.

2. MATERIALS AND METHODS

Five different mortar mixtures, including 0%, 50%, and 100% waste brick and glass used as replacements (by weight) for natural aggregates, were used in this study, as presented in Table 1.

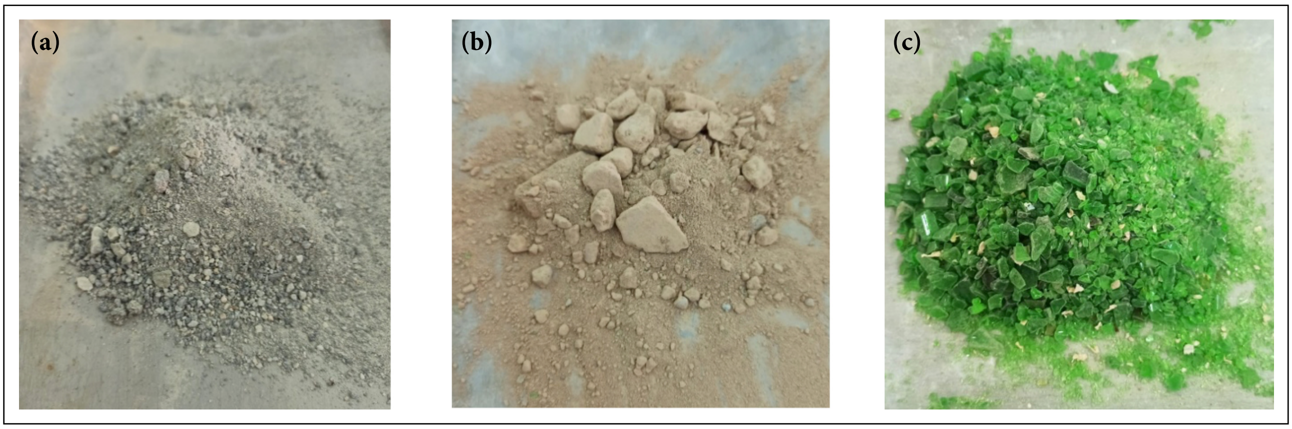

Figure 2. **(a)** Natural fine aggregates. **(b)** Crushed waste bricks. **(c)** Crushed waste glass.

Table 2. Quantities of materials used in the manufacture of each cement mortar mix

Aggregate particle size	Water (kg/m³)	Cement (kg/m³)	Natural (quarried) fine aggregates (kg/m³)				Waste fine aggregates (waste bricks /waste glass) (kg/m³)			
			0.15 mm	0.3 mm	0.6 mm	1.18 mm	0.15 mm	0.3 mm	0.6 mm	1.18 mm
Mix 1 (control set)	367	611	122	244	367	489	0	0	0	0
Mix 2a (50% waste brick aggregates)	530	726	47	93	142	189	47	93	142	189
Mix 2b (100% waste brick aggregates)	541	721	0	0	0	0	94	187	281	375
Mix 3a (50% waste glass aggregates)	392	603	60	121	181	241	60	121	181	241
Mix 3b (100% waste glass aggregates)	367	611	0	0	0	0	122	244	367	489

Indeed, the workability of a cement mortar mixture is one of its most essential characteristics since it directly affects the practical applications of the mortar on the construction site. A mortar that is not satisfactorily workable is generally not preferred to be used on the site. Its rather difficult application might also affect its proper placement and final strength properties if used. Results of the literature survey showed that 35 35-second flow duration is accepted as an efficient flow according to ASTM-C939, and it also indicates that the efflux time for pure water is 8 seconds. Consequently, the optimum efflux time for cement mortar is between 8 seconds and 35 seconds, where higher efflux time means lower flowability and workability [12]. Also, results of the previous work [13] forming the basis for this study showed that cement mortars having 35 seconds of flow according to ASTM C939 yielded a slump interval of 260–270 mm with Abrams cone according to ASTM C143 procedure [14]. Hence, this slump interval of 260–270 mm was selected as the specified workability range for all mortar mixes, and with several trial batches, the quantity of water to be added to each mix was determined to yield this specified slump value [15].

CEM I 42,5 R cement conforming EN 197-1 [16], having a reported specific gravity value of 3.15 g/cm³ was used for all mortar mixes in this study. Natural aggregates were obtained from the active quarries in the Beşparmak (Pentadaktylos) Mountains of Cyprus, where this study was carried out. Waste bricks and glasses used in this study were wastes collected from nature from North Cyprus. The experimental results presented in this study are a fraction of a broader experimental campaign carried out within the same institution. The gravities of waste bricks and glasses obtained from varying sources used in the experimental campaign ranged between 1.95–2.25 for waste bricks and 2.40–2.53 for waste glass used in the mixes. The natural (i.e., quarried) sand used in this study had a specific gravity of 2.64, which the supplier company reported.

After being collected and cleaned from other impurities, waste bricks and glass were crushed in the laboratory and sieved following the EN 933-1 (2012) procedure [17]. For all types of aggregates, the gradation of particles was maintained between the upper and lower content limits defined for the 0.15 mm–1.18 mm size range, following the specifications described in BS 882:1992 [18]. Figure 2a–c illustrate the natural and the recycled (i.e., waste) fine aggregates used in this study.

Table 2 summarizes the exact quantities of all materials used for this study's five distinct mortar mixes. The mixing procedure for all mortar mixes was conforming EN 00196-1–2005, with all mentioned ingredient contents [19].

Once the fresh mortar is placed on the site and it sets and hardens, its performance is determined according to its behavior and response under loading. The compressive strength behavior of concrete is typically regarded as the most critical indicator of its quality [20–22], which is known to be the case for cement mortars. In addition to

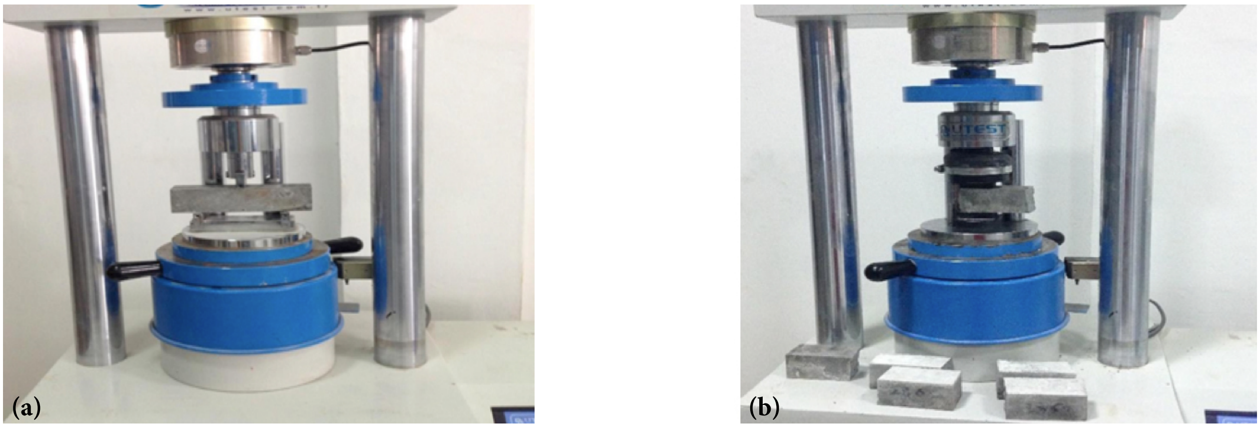

Figure 3. **(a)** Flexural strength testing on mortar prisms. **(b)** Compressive strength testing on halved prisms.

compressive strength, flexural strength behavior will also determine how the mortars would carry on with their service functions since flexural or bending actions could also act frequently on them depending on their service locations on the site. Hence, this study considers compressive and flexural strength testing to observe the efficiency of using waste glass and bricks in cement mortars concerning their hardened-state performance.

Six mortar bars having 40 mm x 40 mm x 160 mm dimensions were produced for each mortar mix. Samples were cast and compacted following the EN 196-1:2005 standard procedure and cured until the testing age [19]. Three of these six bars of each mix were tested at seven days to observe the early strength behavior of the bars, while the remaining 3 bars of each mix were tested at the age of 28 days.

Mortar bars were initially tested under flexural loading, and then, when the bar failed under flexure, the two halves obtained were tested under compressive loading, conforming EN 196-1:2005 part 1 [23]. Figure 3 a and b shows the mortar bars' Flexural and Compressive strength testing.

3. RESULTS AND DISCUSSIONS

The objective of this research study was to provide directly comparable experimental data for the strength behavior of waste brick and glass, including cement mortars that were produced to perform within the same workability range. For this purpose, trial mortar bars, including each specified waste type and content, were fabricated with different water additions, and the water/cement ratio that provided the specified slump range of 260 mm–270 mm was recorded.

Table 3 shows the determined w/c ratios for each type of mortar mix that yielded the targeted slump range.

It was observed that the use of waste glass as a replacement for natural sand in the mortar mix has not caused any significant increase in the water demand of the mix. Similar findings are also reported in the related literature, and this observed behavior was attributed to the non-porous nature of glass, which yielded deficient water absorption [11].

Table 3. Water/cement ratios yield the targeted workability range and the slump values obtained for each mortar mix

Mix	w/c ratio yielding targeted slump range	Obtained exact slump values (mm)
1	0.6	268
2a	0.73	269
2b	0.75	264
3a	0.65	266
3b	0.60	263

The control set (i.e., Mix 1) and waste glass-containing mixes (i.e., Mix 3 a & b) were observed to yield the targeted slump within a w/c ratio range of 0.6–0.65. On the other hand, the mixes made with waste bricks (i.e., Mix 2 a & b) were observed to have higher water demand; the w/c was determined to be 0.75 as the ratio needed to yield the targeted slump, which is 25% higher compared to the w/c of the control mix (i.e., Mix 1). The increase in the water demand of waste brick-containing mortar mixes observed in this study is expected to be due to the relatively porous texture of bricks compared to the texture of waste glass. A similar observation was reported by investigations of the characteristics of fresh mortars, including up to 20% brick replacement [24]. This study also showed that the presence of waste brick in mortar decreased the mix's slump, as noted in this study. Bektas et al. [8] and Zhu and Zhu [9] also report and confirm that the porous nature of the waste brick aggregates yielded adverse effects on the water demand and the workability characteristics of cement mortars.

3.1. Compressive Strength Test Results

Table 4 demonstrates the compressive strength values determined by testing each mortar mix and the strength decrease tendencies observed in each mix compared to control set samples containing no waste aggregates. Figure 4 illustrates the compressive strength development of all mortar mixes until 28 days. Errors bars are equivalent to one standard deviation.

Table 4. Compressive strength test results for each mortar mix used in this study

	w/c ratio	Compressive strength (MPa) 7 days	Compressive strength decrease compared to Mix 1 (7 days) Average	Compressive strength (MPa) 28 days	Compressive strength decrease compared to Mix 1 (28 days) Average
Mix 1	0.60	35.0	0%	42.0	0%
Mix 2a	0.75	31.0	11.43%	36.0	14.29%
Mix 2b	0.73	23.3	33.43%	29.3	30.24%
Mix 3a	0.60	29.3	16.29%	35.4	15.71%
Mix 3b	0.65	28.9	17.43%	36.2	13.81%

The control set (i.e., Mix 1, having only natural aggregates) is observed to yield the highest compressive strength at both seven days and 28 days. Hence, adding any of these waste materials as a replacement for natural sand was observed to cause a reduction in the overall compressive strength of the samples. For all mixes, the compressive strength was observed to have an increasing tendency with the increasing testing age, which is expected to be due to the ongoing hydration of cement in the mixes. Mix 2a and 2b, which are the samples containing 50% and 100% waste brick aggregates, were observed to have up to a 19% strength decrease between each other (when waste brick content was increased) and up to a 30% strength decrease when compared to the control set, at the age of 28 days. The w/c ratio required to yield the targeted slump was observed to have only a 2% difference between the two mixes having brick waste aggregates. Parallel findings are also reported in the related literature. Bektas et al. [8] and Zhu and Zhu [9] reported reduced compressive strength values for cement mortar samples when waste brick aggregates were added beyond certain contents defined their experimental campaigns, and both studies attributed this observed performance change to the porous nature of waste brick aggregates.

Further studies also reported that increasing the addition of waste brick in the mortar decreased the compressive strength of the cement mortars. It is also reported that the increasing addition of waste brick in the mortar decreased the compressive strength of the cement mortars. In their study, Aboutaleb et al. [25] presented that samples including 0% waste brick have 34 and 47 MPa compressive strength values at 7 and 28 days, but samples containing 100% waste brick have 18 and 35 MPa compressive strength values at 7 and 28 days, respectively; indicating a noticeable decrease in strength with the inclusion of wastes within the mortar. The compressive strength decreases recorded in this way with 100% brick aggregate containing mortars (compared to 0%) were 47.06% and 25.53% for 7 and 28 days, respectively. Another study also indicated that waste brick replacement of natural sand in mortar by up to 25% decreased the compressive strength values of mortars considerably. According to Shakir (2017) [26], samples including % five waste bricks yielded 15.12 and 19.12 MPa compressive strength values at 7 and 28 days. On the other hand, samples containing 25% waste brick yielded 2.4 and 8.16 MPa compressive strength

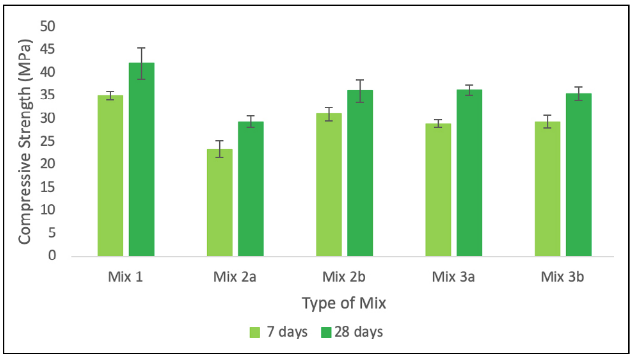

Figure 4. Compressive strength development for each mix between 7 and 28 days.

values at 7 and 28 days, respectively. These results show that the strength decrease was recorded as 84.7% and 57.3% at 7 and 28 days while comparing 5% and 25% brick-containing samples, respectively. The results are in parallel with the results presented in the research conducted. Demir et al. [27] indicate that the compressive strength of the mortar, including 50% waste brick and 50% natural sand, is approximately 31 MPa. The mortar, which included 100% waste brick, had a 7.8% lower compressive strength than the mortar containing 50% waste brick. Hence, the compressive strength of the mortar is reported to decrease with an increased percentage of waste brick inclusion in other studies as well. To illustrate, samples containing %0 waste brick have 33.5 and 42.5 MPa compressive strength values at 7 and 28 days, while samples containing %15 waste brick have 28.8 and 38 MPa compressive strength values at 7 and 28 days, respectively. The results show that strength decreases as much as % 14.03 and % 10.59 at 7 and 28 days while comparing %0 and %15 brick content samples, respectively.

On the other hand, Mix 3a and 3b, the samples having 50% and 100% waste glass aggregates, respectively, were observed to yield only a 3% strength difference at the age of 28 days, even though the waste glass aggregate content was doubled with Mix 3b. Moreover, with these mixed contents, Mix 3b, which has more waste aggregate, is observed to yield slightly higher compressive strength. When the water/cement ratios of the two mixes were compared, the reason for this slight increase could be potentially attributed to the lower w/c ratio of the mix 3b, which was sufficient to yield the targeted slump. Hence, these results indicate that the difference in the water content of the mixtures has a relatively more governing effect; even though the waste content was increased, the lower water content of the mix could positively affect the ultimate compressive strength determined at the age of 28 days. The waste glass aggregate-containing mixes (Mix 3a & 3b) were observed to yield up to a 16% strength decrease in general compared to "no waste-containing" Mix 1 samples at 28 days. This decrease of 16% with waste glass aggregates inclusion (when compared to Mix 1) could be considered as approximately half of the 30% strength decrease (compared to Mix 1) that was observed with the samples that contained waste brick aggregates (i.e., Mix 2a & 2b). Waste glass aggregate inclusion in the mortar bars was reported to yield a decrease in the compressive strength of mortars, as reported in the related literature. Similar studies also report a negative effect on compressive strength upon adding waste brick aggregates. The results presented by Bhandari et al. [28] indicated that compressive strength values for mortar samples, including 20% waste glass, experienced around an 18% strength decrease compared to the case of not using waste aggregates. Additionally, Darshita and Anoop reported a 17% compressive strength decrease when 50% of the aggregates in the mortars were replaced with waste glass aggregates [29].

Mix 2b used in this study, having 100% waste brick aggregates, yielded the lowest compressive strength value, 29.3MPa at 28 days, among all mixes. Even though the type of waste aggregate is expected to be one of the causes of this strength decrease, it is also expected that the unavoidable increase in the water demand of this mix also played a considerable role in the observed reduction in strength. Nevertheless, this increase in the water demand is attributed to the "type" of the waste aggregate since the relatively more porous texture of the brick could be observed when compared to the waste glass aggregates.

Similar to the case in concrete, compressive strength values of mortars are accepted as the main indicator of material quality.

The standard ASTM C270 [30] provides specifications for cement mortars and defines four categories, namely M, S, N, and O types of mortars for different site applications. Among these, type M mortar is defined for uses that require especially high compressive strength, and the mentioned standard defines its strength requirement as a minimum of 17.2MPa. In contrast, type N mortar, known to be used for general-purpose applications, is determined to have a compressive strength of 5.2 MPa in 28 days. As shown in Table 4, all mortar mixes used in this study are observed to yield 28-day compressive strength values that are well beyond the real application requirements defined in ASTM C270 [30]. Mix 2b (50% brick aggregate) and Mix 3b (50% glass aggregate) mortar mixtures proposed and tested within this study yielded 29.3MPa and 36.2MPa strength values, respectively, which enables them to be safely eligible to be used in the site applications according to the standards.

On the other hand, it is known that engineering applications require optimization in materials selection and quantity determination to meet criteria regarding safety and economy, which are both essential. In this study, the research priority and scope have been defined as providing systematical experimental data on *the feasibility of* ***manufacturing cement mortars including up to 100% waste aggregates***, which, *as a first step, considered only the safety aspect of engineering applications* rather than the economy. The achieved strength results within this frame indicate the feasibility of using waste brick and glass aggregates in this preliminary step. The study's next step should focus on manufacturing more economical mortar mixes to eliminate the maximum amount of waste materials. One straightforward approach to reduce the cost is undoubtedly by reducing the cement content of the mix. As the strength values achieved are already higher than commonly expected mortar strength values (based on mortar strength performance defined in ASTM C270), reducing cement content up to a certain level is expected to be tolerated. However, detailed studies should be employed to verify the optimum cement content to be used with maximum allowable waste content while obtaining safe and economical mortar mixes.

3.2. Flexural Strength Results

Table 5 demonstrates the flexural strength values yielded by each mortar mix and the strength decrease tendencies compared to control set samples that contained no waste aggregates, where Figure 5 illustrates the flexural strength development of all mortar mixes between the ages of 7 and 28 days, in comparison with each other. Errors bars are equivalent to one standard deviation.

As was observed within the compressive strength development of the mortar samples, Mix-1 yielded the highest flexural strength values at each testing age compared to the values obtained by other mixes containing waste aggregates. Even though the lowest flexural strength values recorded at the periods of 7 and 28 days were both yielded by 100% waste glass aggregate-containing mix 3b, it was noted that the strength values yielded by Mix 3b, 3a, and 2b were significantly close to each other. Mix 2a was observed to stand out from the rest of the waste aggregate-containing mortar mixes while yielding the second-highest strength values, following the control mix.

In another study, Abbas (2017) [31] indicates that it is also reported that the presence of %30 waste glass content in the samples generally yielded slightly negative effects on the flexural strength development of mortars. Their results demonstrated that flexural strength values for samples, including 30% waste glass, decreased to 1.37% compared to their control mixture. According to Tuaum (2018) [32], The research also investigated the flexural strength behavior of mortar specimens made with CEM I cement and reported that the lowest flexural strength value for 50% waste glass replacement was approximately 9 MPa at 28 days, which is highly by the results presented in the research. In addition, the study reports up to 11.76% flexural strength decrease at 28 days using 50% waste glass aggregates compared to their control set.

Table 5. Flexural strength test results for each mortar mix used in this study

	w/c	Flexural strength (MPa) seven days	Flexural strength decrease compared to Mix 1 (7 days) Average	Flexural strength (MPa) 28 days	Flexural strength reduce compared to Mix 1 (28 days) Average
Mix 1	0.6	8.1	–	9	–
Mix 2a	0.75	5.8	28.40%	6.6	26.67%
Mix 2b	0.73	4.9	39.51%	5.7	36.67%
Mix 3a	0.6	4.8	40.74%	5.6	37.78%
Mix 3b	0.65	4.3	46.91%	5.5	38.89%

Even though the 50% waste brick aggregate-containing Mix 2a and 50% waste glass aggregate-containing Mix 3b were observed to yield very similar compressive strength values, their flexural strength values were observed to differ; since mix 2a's flexural strength value was higher even though it contained higher water content. This behavior could be attributed to the rougher surface texture of the waste brick aggregates compared to the texture of glass aggregates, as the bonding between the aggregate and the cement paste is expected to be enhanced with the increased surface texture of the aggregates. Compressive strength testing is primarily affected by the mortar mixture's porosity. Hence, the effects of the water/cement ratio of the mortar, the general strength of the mortar, and the strength of aggregates are detectable with compressive strength testing. On the other hand, flexural strength testing is known to be more likely to reveal any strength decrease due to lack of bonding of the aggregates since the action of bending the samples would quickly cause detachment of aggregates and the paste very quickly, in case there is lack of adhesion due to aggregates' surface texture [33]. Highly parallel findings were also presented by Tan and Du (2013) [10] and Lu and Poon (2018) [11], as mentioned earlier within the literature information presented in the introduction section. These studies reported that the smooth surface texture of the glass aggregate yielded weaker bonds between the glass aggregate and the cement paste and hence yielded lower splitting tensile strength (known to be correlated with the flexural strength) of the mortar samples tested. Therefore, the difference between the surface texture of glass and brick aggregates and their influence on the mortars' performance should also be evaluated with flexural strength testing observations.

Concrete flexural strength is 10–20% of its compressive strength as a general tendency [33–35]. Mortar behavior is not directly equivalent to concrete behavior; however, a coherent behavior of cement-based materials could reasonably be expected. Within this frame, the 28-day flexural strength values observed for all mortar mixes manufactured in this study yielded a performance higher than at least 16% of their recorded compressive strength. In this case, the obtained results confirm that yielded flexural strength performance is coherent with the engineering performance expectations, especially considering that their compressive strength values are much higher than the high-strength Type M cement mortars defined in ASTM C270.

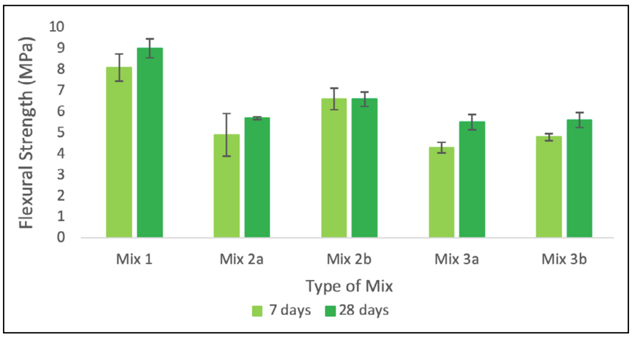

Figure 5. Flexural strength development for each mix at the ages of 7 and 28 days.

4. CONCLUSIVE REMARKS AND RECOMMENDATIONS FOR FUTURE STUDIES

This study investigates the effects of using recycled brick and glass aggregates as a replacement for natural sands used in cement mortars quantitatively and comparably. Recycling waste materials is critical for preserving nature and natural resources and is a key to sustainable development. On the other hand, waste materials within cement mortars, a very widely used construction material, would be considered feasible and acceptable only if the obtained performance could satisfy the civil engineering needs at least at a satisfactory level.

The systematical experimental studies carried out on cement mortars that included waste glass and bricks separately, at %50 and 100% replacement ratios, provided the following quantitative comparisons and conclusive remarks:

I- Using recycled brick aggregates to replace natural sand in the mortar mixes caused a higher water demand to yield the specified workability characteristics when compared with the help of recycled glass aggregates. This is expected to be due to the increased absorption of brick aggregates, which are observed to be relatively more porous.

II- The necessity to increase the water content of the mortar mix with brick aggregates to obtain a satisfactorily workable mix had negative effects on the observed compressive strength behavior yielded by the mortar samples. The minimum compressive strength was obtained with the samples with 100% waste brick aggregates; these samples, on average, yielded a 30% compressive strength decrease compared to the control mix with no waste addition.

III- The mortar samples, including waste glass aggregates, were observed to yield higher compressive strength values. The decrease in compressive strength yielded by 100% waste glass aggregate inclusion into the mortars was only up to 16% compared to the control mix, which could be considered half of the strength decrease yielded when using brick aggregates. The compressive strength performance exhibited by samples with 100% waste glass is very similar to those with waste brick aggregates up to 50%.

IV- When the flexural strength testing results were considered, it was observed that the samples made with waste glass aggregates inclusion yielded much lower strength performance compared to the samples made with waste brick aggregates. The total strength decrease (compared to the control set) recorded for samples having 100% waste glass aggregates is up to almost 39%. This behavior is expected to be due to potentially reduced bonding between the paste and the glass aggregates, which have relatively smooth surface texture compared to the brick aggregates with rougher surface texture.

V- When compared with the standard specifications provided in ASTM C270 defining minimum compressive strength performance expected from cement mortars for real engineering applications on-site, all mortar mixes, including the ones with 50% waste aggregate replacements, have been observed to perform satisfactorily regarding the needs of engineering applications. Additionally, the flexural strength performance of all mortar mixes used in this study was greater than at least 16% of each mix's compressive strength, indicating coherence with the general engineering expectations. Hence, the proposed mortar mixes with up to 50% (by mass) waste aggregate replacement have been observed to be suitable for real engineering applications.

VI- The obtained experimental results show that the type of waste aggregate for cement mortars should be selected considering the specific service location of the mortar used in the construction applications and their designed functions. If the mortar is required to perform well, specifically under compressive loads in the construction site, using waste glass aggregates in the mortar mix, even with high percentages, would yield better performance than waste brick aggregates. On the other hand, if the mortar is required to perform well, specifically under flexural actions in the construction site, the use of waste brick aggregates in the mortar mix, even with high percentages, is expected to perform better under these conditions.

In this way, eliminating higher quantities of waste (through being used in construction materials) would be possible without sacrificing the required engineering performance.

As recommendations for future studies, using further waste brick and glass aggregates with varying ages and properties is expected to yield significant insights into the effects of waste aggregates on cement mortars. Carrying out systematical experiments to determine the characteristics of waste aggregate particles, such as their specific gravity and absorption capacities, would be essential to relate their observed consequences on mortars, mainly if several samples of the same waste type (brick or glass) are employed with varying ages and conditions. Including these waste aggregates with different percentages is also recommended to provide an extended range of experimental data sets. Future studies should also consider carrying out systematical investigations on the optimum cement content that will be used in such mortars together with waste aggregates to provide both safe and economical site applications of mortars. Moreover, the segregation likelihood of the mortar mixes and effects of the characteristics of materials selected to be used should studied as well to provide more complete data that will be beneficial, especially for the actual site applications. Finally, in addition to the fresh and hardened mortar properties such as workability and strength, complementary SEM analyses are recommended for future studies to relate further the surface texture and bonding characteristics of each waste aggregate employed to the ultimately observed mortar properties.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

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