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Research Paper

Producing Sustainable Cement Mortar by Replacing Sand with Waste Bottle Glass

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ABSTRACT

This study investigates the possibility of using waste bottle glass to replace natural sand within cement mortar. This research promotes ecologically conscious and sustainable building methods. The experimental program of the study included several cement mortar mixes that were cast by using two main (c:s) ratios (1:2 and 1:3). Every mix kept a constant 0.5 water/cement ratio. The crushed recycled waste bottle glasses find application in various replacement ratios ranging from 5% to 100%. Important characteristics, including workability, compressive strength, tensile strength, flexural strength, and flexural modulus, are evaluated in this work. The findings show that adding 10–15% glass to 1:2 mixtures significantly increases their ductility and mechanical strength. Furthermore, under ideal circumstances, complete replacement (100%) turned out to be structurally possible. Due to excessive fines and inadequate cohesion, workability decreased in 1:3 mixes, but it increased significantly in low-glass 1:2 mixes. At last, the study results indicate that this work considers a workable solution for using waste bottle glass as a sand replacement in mortar. This method solves problems with disposing of glass and makes us less reliant on natural sand. The proposed mix designs are a good alternative for environmentally friendly material development in the construction industry. They also support the principles of the circular economy.

1 Introduction

Given the growing importance of both sustainability and environmental protection, it is essential to take these into consideration in construction techniques. Glass is closely used in various aspects of daily life, including buildings, soft drink containers, prescription bottles, automobiles, mirrors, windshields, doors, windows, ornamental items, tube lights, bulbs, and other electronics. The disposal of broken waste glass, which ends up in landfills, is becoming a serious environmental problem, especially in countries with limited landfill capacity [1, 2]. Each year, large amounts of waste glass are disposed of in landfills due to the high cost of disposal materials, limited opportunities for glass recycling, and various other factors [3, 4]. This issue has intensified the global interest in exploring sustainable alternatives for reusing and recycling waste glass.

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Consequently, efforts to develop a sustainable method to reuse and recycle glass have intensified in recent years. Global research studies have shown that glass cullet can partially replace sand in construction materials [5, 6]. Several experimental research projects have examined the feasibility of utilizing waste glass, especially in cullet or powdered form, as a partial substitute for aggregate or cement in concrete or mortar mixtures. These studies have reported a varying range of effects on the mechanical and durability properties of mortar and concrete, depending on the particle size, replacement ratio, and material type [7–10]. Among promising future uses, a novel method for incorporating waste glass powder into concrete significantly enhances compressive and flexural strength. This is due to improved dispersion and pozzolanic activity [11]. The chemical composition of waste glass, pozzolanic activity, micro-filler effects, and their impact on the interfacial transition zone properties and the hydration behavior have been studied [12–13]. Issues such as alkali-silica reaction (ASR), porosity, and bonding defects can sometimes limit the use of waste glass at higher replacement levels [14, 15]. The possible use of waste glass in cement manufacture has been shown to improve compressive and tensile strengths in concrete, and glass powder and palm kernel shells have shown potential as environmentally friendly substitutes [16]. Research indicates that recycled glass improves compressive strength and impermeability when used at certain percentages, particularly when ground to particle sizes below 75 μm . Recycled glass increases compressive strength compared to the standard mixes used at specific percentages, especially at the 20% replacement level, which has been shown to improve hydration, reduce porosity, and enhance mechanical performance [17 – 20]. The mechanical behavior of concrete crushed waste glass as a substitute for coarse and fine aggregates has revealed improvements in compressive strength and energy absorption capacity [21]. The good fire and thermophysical properties of glass powder make it a suitable material in thermally demanding construction [22, 23]. Waste glass powder has also shown a significant increase in flexural strength, particularly at low replacement ratios, indicating its effectiveness in enhancing structural ductility in reinforced concrete beams [24]. There are numerous different experimental studies that have further verified the feasibility of using enlarged glass aggregates (EGA) and nano-supplemented glass for improved thermal insulation and strength [25, 26], demonstrating its applicability as a sustainable substitute in clinker formulation and lowering CO₂ emissions [27]. Cement mortars, which include ground waste glass and other pozzolanic materials such as silica fume, marble powder, or polymeric additives, have exhibited increases in terms of strength, ductility, and environmental impact reduction. A novel eco-friendly concrete mixture with increased performance has been presented, using an optimized mix of waste glass powder and waste glass sand as cement and fine aggregate replacements, respectively [28–31]. Particularly in fine aggregate substitution strategies, adding polymer, demolition, and glass waste into concrete has resulted in cost reduction, improved durability, and alignment with sustainable development goals [32]. Using toughened waste glass aggregate in concrete has demonstrated resistance to hostile conditions and outperforms conventional aggregates in specific applications [33]. Recent research in Iraq has explored the possibilities for incorporating glass waste into concrete mixtures. Some results indicated that, while meeting local criteria, up to 30% waste glass powder can replace sand without compromising strength or workability [34]. Furthermore, incorporating glass in cement-based products offers a workable solution for problems facing the cement industry, including CO₂ emissions, energy consumption, and raw material depletion [35, 36]. Still, most of these studies have focused on substituting concrete instead of mortar or on glass powder alone in mortars [37–38], the majority utilized rather low replacement percentages (5% to 25%) and lacked comprehensive evaluation of mechanical performance across a whole range of substitution levels. Moreover, although the effects of glass as a substitute for cement have been extensively investigated, less attention has been given to its function as either a complete or partial replacement for fine aggregates in cement mortars. Few studies have assessed, using real load-deflection behavior, the impact of waste bottle glass on flowability, tensile and flexural strength, or flexural modulus. An integrated study on the mechanical behavior and practical feasibility of using waste bottle glass as an aggregate replacement in cement mortars remains lacking.

Despite a lot of research having been done on the use of waste glass in cementitious materials, there is a shortage of studies that explored the use of crushed waste bottle glass as both a complete (100%) and partial sand incorporation, while also assessing its cost-effectiveness, sustainability, lower CO₂ emission, and mechanical performance. This approach differs from earlier studies, which either examined limited replacement ratios (<50%) or primarily utilized glass powder as a cement substitute. This shortcoming in previous studies leaves a clear gap in understanding the possibility of incorporating waste bottle glass in mortar.

This experimental study addresses this research significance of the gap concerning the use of waste bottle glasses as sand replacement in cement mortar by systematically investigating the mechanical features of cement mortar using recycled waste bottle glass as partial or all of the natural sand. Two main mix ratios of 1:2 and 1:3 (cement to sand) were tested with a constant water/cement ratio of 0.5 and sand replacement levels varying from 5% to 100%. The study considered both hardened and fresh properties, like the flow table (which measures workability), compressive, tensile, and flexural strength,

flexural modulus, and how the load-deflection behavior changes. This experimental study aims to identify the optimal replacement ratio of natural sand in cement mortar with waste bottle glass, which can be used to produce sustainable cement mortar for environmentally friendly constructions. By guaranteeing the appropriate balance between the fresh and hardened characteristics. The findings of this study will also help to improve sustainable construction methods, effective recycling practices (waste management), and circular economy practices.

2 Experimental Program

This work aims to investigate the effects of substituting recycled waste bottle glass for natural sand on the properties of cement mortar. While keeping a constant water/cement ratio of 0.5 across all mixtures to isolate the variable effect of waste bottle glass substitution. Two cement-to-sand mix ratios, 1:2 and 1:3, were selected to evaluate mechanical behavior under varying fine aggregate volumes. Sixteen mixes were made with waste bottle glass substituted at 0%, 5%, 10%, 15%, 20%, 25%, 50%, and 100% by weight of natural sand. Fig. 1 demonstrated the primary methodological approach of this experimental study.

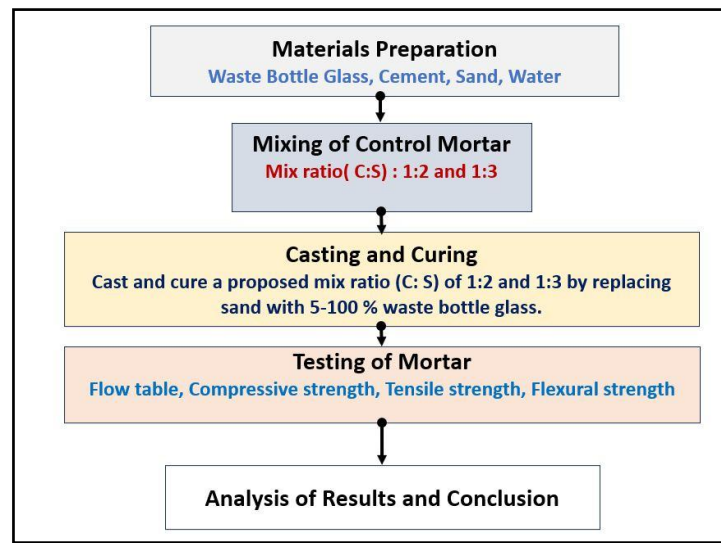


Fig. 1- Methodological approach

2.1 Material Properties

2.1.1 Fine Aggregate

Fine aggregate (sand) locally available natural silica sand was utilized in all mortar mixes as fine aggregate. Its grading was tested according to Iraqi standards (IRQ No. 30/1984). The fineness modulus was determined according to ASTM C33M/13. The results satisfy Iraqi standards (IQS No.45/1984) as presented in Table 1.

Table 1. Grading test results for sand.

Sieve no. [mm]	Total retained [%]	Total passing [%]	Limitations of the IQS no. 45/1984—region no. 2
10 [mm]	0	100	100
4.75 [mm]	0	100	90-100
2.36 [mm]	9	91	75-100
1.18 [mm]	15	85	55-90
600 [micron]	40	60	35-59
300 [micron]	76	24	8-30
150 [micron]	92	8	0-10
Material finer than 75 microns	1.1		5% max
The modulus of fineness	2.32		[2.3-3.1] ASTM C33M/13

2.1.2 Cement

Throughout the experimental work, all mixes were prepared with traditional Portland cement (I). It was stored in a dry area to avoid interaction with severe weather conditions. The physical and mechanical characteristics of cement were investigated according to the Iraqi Reference Guide (198-1990), and the chemical composition was tested based on the Iraqi Reference Guide (472-1993). Table 2 and Table 3 present the chemical composition and physical characteristics of cement, respectively. The results are compliant with Iraqi standards (IQS No.5/2019).

Table 2. Chemical properties of cement.

Chemical property	Content [%]	Limit of IQS No.5/2019
MgO	2.65	$\leq 5\%$
SO ₃	1.95	$\leq 2.8\%$
Loss of ignition	3.02	$\leq 4\%$
Insoluble materials	1.04	$\leq 1.5\%$
Lime saturation factor	0.85	0.66 – 1.02

Table 3. Physical and mechanical properties for cement material.

Mechanical and physical properties	Result	Limit of IQS No.5/2019
Fineness [m ² /kg]	255.98	≥ 250
Setting time		
Initial [hour : minute]	0:60	≥ 45 minutes
Final [hour : minute]	8:10	≤ 10 hours
Compressive strength [MPa]		
2 days	12.0	≥ 10
28 days	33.0	≥ 32.5

2.1.3 Water

In the present experimental work, all mortars were mixed using drinking water, as well as to cure specimens and do other material tests. The water used satisfied the Iraqi specification (IQS 1703/2018).

2.1.4 Waste bottle glass

Glass from colorless waste bottles has been collected for this study from both commercial and residential sources. After the collecting process, the glass was carefully cleaned, cleared of impurities, and allowed to air dry. A Los Angeles abrasion machine was then used to crush the dried glass into small fragments, as seen in Fig. 2.



Fig. 2 - The Los Angeles device crushed the bottle glass into fine, small fragments.

Through this process, the glass was reduced to a size suitable for use in mortar as a sand replacement. Subsequently, a mechanical sieve shaker was used for sieve analysis, and the particle distribution was noticed to match Zone No. 2 of IQS No. 45/1984 (Table 4 and Fig. 3).

Table 4: Grading test results of waste bottle glass.

Sieve size	Cumulative retained [%]	Cumulative passing [%]	Limit of IQS No.45/1984- Zone No.2
10 [mm]	0	100	100
4.75 [mm]	0	100	90-100
2.36 [mm]	0	100	75-100
1.18 [mm]	8.91	91.09	55-90
600 [micron]	55.45	44.55	35-59
300 [micron]	79.21	20.79	8-30
150 [micron]	94.06	5.94	0-10
Material smaller than 75 microns	0.99		5% max
The modulus of fineness	2.376		(2.3-3.1) ASTM C33/86



Fig. 3 - Sieve analysis for crushed waste glass.

The analysis verified that the crushed waste bottle glass was suitable as a fine aggregate. The EDS test was used to validate the chemical compatibility of the waste bottle glass with mortar mix utilizing a chemical composition study. The results identified that waste bottle glass is of the soda-lime glass family, and this is the most often used type in drink bottles, with minor amounts of aluminium oxide (Al_2O_3) and other oxides. The results of the EDS indicated that silicon dioxide (SiO_2) at roughly 71.2%, sodium oxide (Na_2O) at 13.3%, and calcium oxide (CaO) at 9.3% were the principal components, as presented in Table 5.

Table 5: Chemical composition of waste bottle glass.

Material oxide	Symbol	Content (%)
Silicon dioxide	SiO_2	71.2
Sodium oxide	Na_2O	13.3
Calcium oxide	CaO	9.3
Magnesium oxide	MgO	3.0
Aluminium oxide	Al_2O_3	1.1
Iron oxide	Fe_2O_3	0.4
Potassium oxide	K_2O	0.6
Others & trace elements	-	1.1

According to the previous studies, as these values fall within the composition ranges reported by Czapik et al. [20], these results are appropriate for the fit of the waste bottle glass for either full or partial sand replacement since their chemical structure and reactivity match those of earlier investigations of glass in cementitious materials. The information also supports the idea that, when finely crushed, soda-lime waste glass can either act as an inert filler or provide pozzolanic effects.

2.2 Trail mixes

Sixteen different mix proportions were examined to examine how waste bottle glass influences the cement mixture. The standard ratios for cement to sand are 1:2 and 1:3, and a constant ratio of water to cement is 0.5. Various portions of waste glass were used to replace sand by weight and were utilized for investigating the mechanical properties of the mortar at ages 7 and 28 days, as well as to create a flowable, high-strength, and sustainable cement mortar from waste glass. Table 6 presents all sixteen mixture proportions used to prepare the trail mixes. Fig. 4(a) to 4(e) illustrate the processes utilized to create all of the trail mix. Twenty-eight days and seven days before the planned testing day, each of the samples was cleaned and set up for testing, with the results acquired during the test.

Table 6- Details of mortar mixtures.

No.	C (Cement): S (Sand): G (Waste glass) %	W/C
M-1	1:2:0	0.5
M-2	1:3:0	0.5
M-3	1:2:5	0.5
M-4	1:3:5	0.5
M-5	1:2:10	0.5
M-6	1:3:10	0.5
M-7	1:2:15	0.5
M-8	1:3:15	0.5
M-9	1:2:20	0.5
M-10	1:3:20	0.5
M-11	1:2:25	0.5
M-12	1:3:25	0.5
M-13	1:2:50	0.5
M-14	1:3:50	0.5
M-15	1:2:100	0.5
M-16	1:3:100	0.5



Fig. 4(a)- Weigh all the materials and prepare the crushed waste glass for mixing together.



Fig. 4(b)- Before adding cement and water, mix the sand and crushed waste glass.



Fig. 4(c)- Before adding water, ensure that you mix the dry ingredients thoroughly.



Fig. 4(d)- Mix the dry ingredients with the water once it's poured.



Fig. 4(e)- Pouring mortar into the form and then curing it.

Fig 4- The processes utilized to create all of the trail mix

2.3 Testing procedure

2.3.1 Flow table test

Test specimens for the flow table were conducted to determine the indication of the workability of all mixtures. The test approach has investigated the flow of hydraulic cement mortars in accordance with ASTM C1437, as shown in Fig. 5.



(a) Flow table apparatus.



(b) Flow table test measurements.

Fig. 5 - Flow table test set-up

2.3.2 Compressive strength test

A hydraulic compression testing machine with an 1800 kN capacity was used to measure the compressive strength of the mortar specimens at 7 and 28 days of curing. All mixes were cast into standard cube specimens with dimensions of $50 \times 50 \times 50$ mm. The test was performed by ASTM C109M. Each specimen was carefully positioned in the testing machine, and a steady load was applied until failure occurred. The compressive strength, in MPa, was calculated based on the recorded maximum load. Fig. 6 illustrates the arrangement of the test.



Fig. 6- Compressive strength test

2.3.3 Tensile test

Testing standard briquette-shaped specimens cast for each mix using a hydraulic compression machine with a capacity of 5 kN enables one to determine the tensile strength of the cement mortar. ASTM C307. Every briquette specimen has been exactly aligned in the machine testing, and the load was applied gradually till failure. At that point of failure, the peak load was recorded, and tensile strength was calculated accordingly. Fig. 7 shows the test process and instrument arrangement.



Fig. 7 - Tensile test according to ASTM C307.

2.3.4 Flexural test

Following ASTM C348, the flexural strength of the mortar specimens has been evaluated using a hydraulic compression machine with a 5 kN capacity. This machine was also used in the tensile tests. Each mix used standard prism specimens measuring 160 x 40 x 40 mm. To determine the load-deflection behavior of every mix, a 50 mm dial gauge was installed to monitor the mid-span deflection during loading. Fig. 8 shows the test setting and procedure.



Fig. 8 - Flexural strength test according to ASTM C348.

3 Results and discussions

The flow table, compressive strength, tensile and flexural strength test, and load-deflection curve analysis for each mixture are all thoroughly conducted and discussed. The mechanical properties of cement mortar when a partial or total replacement of sand is substituted with waste bottle glass were examined to determine the optimal glass-to-sand replacement

ratio. In order to assess the feasibility of using bottle glass waste as a substitute for sand in the creation of sustainable mortar, the results are compared to those of the reference mixes.

3.1 Flow table results

The following Table 7 presents the flow-table test results for all the mixtures along with the detailed observations particular to each. The results of the test depict that, depending on the cement-to-sand ratio and replacement of waste bottle glass ratio, the workability behavior is affected when natural sand is substituted with waste bottle glass. In comparison to the reference mix M-1, it was noted that at low to moderate substitute waste bottle glass replacement percentages (5–20%), the flow table values are improved for mixes with a C:S ratio of 1:2 (M-series: M-1, M-3, M-5, M-7, M-9, M-11, M-13, and M-15), with a maximum increase reaching 1.339%. Higher waste bottle glass replacement ratios (50%–100%), however, caused a noticeable reduction in flowability, particularly in M-9 to M-15, with decreases ranging from 18.446% to 33.252% relative to M-1. In contrast, as the glass content increased, the 1:3 mixes (M-2 as the reference and M-4 to M-16) continuously showed decreasing flow values. Mix M-14 showed reductions of up to 77.450%, indicating that mortar mixtures with a higher proportion of sand and a lower cement proportion are more vulnerable to the smooth surface texture and angularity of glass particles, which weaken paste cohesion and impede workability. Fig. 9 shows the influence of waste bottle glass replacement on workability in mortar with varying cement-to-sand ratios (1:2 and 1:3). Mixes with a 1:3 ratio exhibited a significant decrease in flow table results even at low waste glass substitute, while trial mix groups with a 1:2 ratio demonstrated the highest level of workability at about a 10–15% replacement ratio. These findings suggest that the influence of waste bottle glass on workability is largely determined by the sand content of the mix and that adding glass in large quantities may result in reduced workability in smaller sand-containing mixtures. Overall, the results indicate that using waste bottle glass as a sand replacement in mortar, especially between 10% and 20% for mixes with a C:S = 1:2 ratio, offers acceptable workability without sacrificing fresh-state qualities. However, due to poor cohesion and increased surface area demand, even a small amount of glass acceptance in leaner mixes (1:3) may negatively impact workability.

Table 7: The flow table test results for all the mixtures.

No.	C (cement): S (sand): W (waste glass) %	W/c	Flow value (%)
M-1	1:2:0	0.5	103
M-2	1:3:0	0.5	102
M-3	1:2:5	0.5	105.75
M-4	1:3:5	0.5	34
M-5	1:2:10	0.5	138
M-6	1:3:10	0.5	32.5
M-7	1:2:15	0.5	116.75
M-8	1:3:15	0.5	55
M-9	1:2:20	0.5	75
M-10	1:3:20	0.5	28.5
M-11	1:2:25	0.5	68.75
M-12	1:3:25	0.5	51.25
M-13	1:2:50	0.5	84
M-14	1:3:50	0.5	23
M-15	1:2:100	0.5	89.75
M-16	1:3:100	0.5	101.75

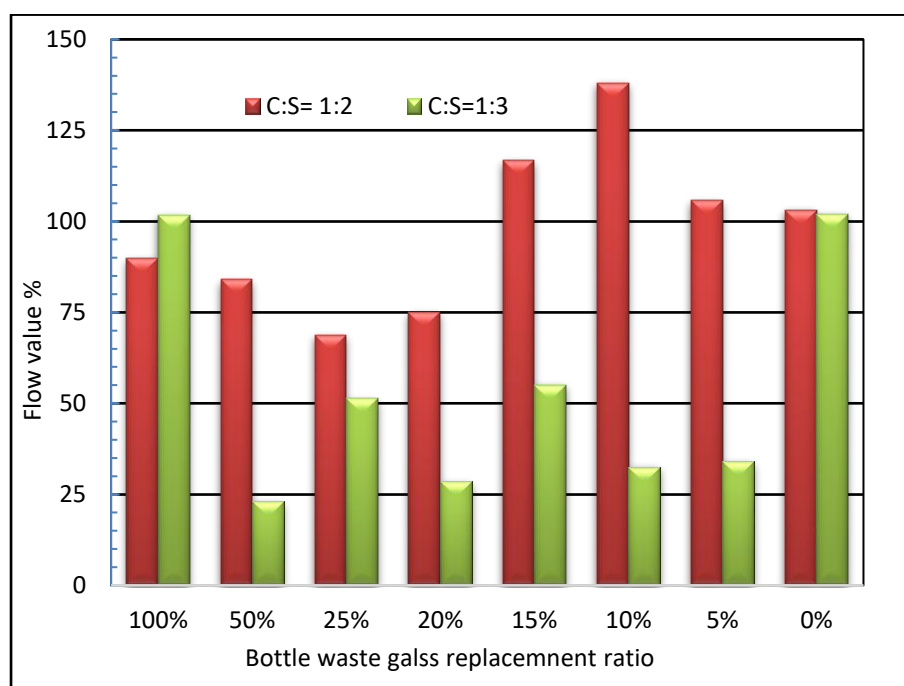


Fig. 9 - The impact of bottle waste glass replacement ratios on the workability of various mixtures

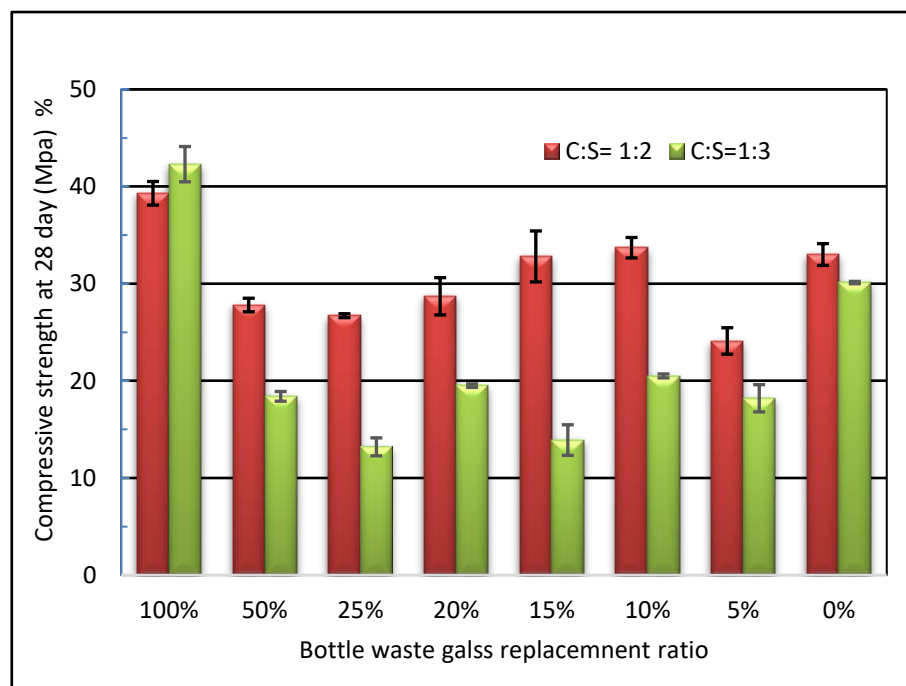
3.2 Compressive strength

Table 8 presents a summary of the average 3 cubic compressive strength for all mortar mixes at 7 and 28 days, while Fig. 10 illustrates the results. To illustrate the statistical analysis of the results, the coefficient of variance, standard deviation, and p-values are computed from three specimens for each mix age and included with all reported average strengths. The Fig. 10 error bars demonstrated the ($\pm$) standard deviation (SD) for samples in each mix. Compressive strength increased with curing time in all mixes, as expected. The mixes group with a c:s ratio of 1:2 performed better than the 1:3 mixes at almost all replacement ratios because of its higher cement content and improved particle cohesion. The best results were developed through the C:S 1:2 mix group at replacement ratios (10–15%). Comparing mixes M-5 and M-15 to the reference mix shows respective increases of 2.121% and 19.090%, respectively. This suggests that the fine waste bottle glass contributed to densification and may have generated pozzolanic activity. Strength, however, dropped as substitution ratios (e.g., M-9, M-11, M-13) rose; most likely, this was due to poor bonding and increased porosity. On most mixes, the C:S 1:3 group mixes exhibited more marked strength reductions, with drops ranging from 30 to 50% at higher glass contents. M-16 was an exception; it showed a 40.531% increase over its control (M-2), indicating that under ideal conditions, total replacement can still yield reasonable strength (see Fig. 10). Overall, the findings illustrate that waste bottle glass can replace up to 15% of the sand in C:S 1:2 mortars while maintaining their mechanical integrity. Above this threshold, especially in leaner mixes, the detrimental effects on matrix cohesion become apparent. These findings support the feasibility of producing sustainable mortar with appropriate proportions of recycled glass bottles in accordance with environmental and durability goals.

The statistical significance of compressive strength values for each mix was evaluated using an independent t-test ($\alpha = 0.05$) compared to the reference mixes (M-1 for odd-numbered mixes and M-2 for even-numbered mixes) as tabulated in Table 8. Some mixtures, such as M-3, M-6, M-8, M-10, M-12, M-15, and M-16, exhibited significant differences ($p < 0.05$) in the 7-day results, indicating that both low and high replacement ratios can cause measurable changes in early-age strength. At this age, conversely, mixes M-5, M-7, M-9, M-11, M-13, and M-14 showed no statistically significant difference from the control ($p \geq 0.05$). However, mixes M-5, M-7, and M-9 maintained strength values compared with the control at 28 days; the majority of the mixes displayed statistically significant differences from the control ($p\text{-value} < 0.05$). Some mixtures, especially M-3, M-6, M-8, and M-10, have shown significant improvements. This is because the particles are well distributed and the cement and glass stick together well. On the other hand, the decreases seen in others are likely due to damaged interfacial transition zones at high replacement levels.

Table 8: Compressive strength test results and statistical analysis for all the mixtures

No.	C (Cement) : S (Sand) : G (Waste glass) %	W/C	7 days (MPa) Mean $\pm$ SD (n=3)	Coefficien t of variants (%)	7-day compressive strength P- value vs. control mix at $\alpha = 0.05$	28 days (MPa) Mean $\pm$ SD (n=3)	Coefficien t of variants (%)	28-day compressive strength P- value vs. control mix at $\alpha = 0.05$
M-1	1:2:0	0.5	18.1 $\pm$ 2.9	16.1	-	33 $\pm$ 1.2	3.7	-
M-2	1:3:0	0.5	16.2 $\pm$ 1.9	11.8	-	30.1 $\pm$ 1.8	6.0	-
M-3	1:2:5	0.5	12.2 $\pm$ 0.9	7.6	0.029	24.1 $\pm$ 0.7	2.9	0.000
M-4	1:3:5	0.5	11.6 $\pm$ 3.1	26.7	0.094	18.2 $\pm$ 0.5	2.8	0.000
M-5	1:2:10	0.5	17.8 $\pm$ 1.7	9.3	0.885	33.7 $\pm$ 0.2	0.6	0.381
M-6	1:3:10	0.5	9.0 $\pm$ 0.5	6.0	0.003	20.5 $\pm$ 0.9	4.5	0.001
M-7	1:2:15	0.5	17.9 $\pm$ 0.8	4.4	0.911	32.8 $\pm$ 1.9	5.9	0.886
M-8	1:3:15	0.5	6.8 $\pm$ 0.6	9.5	0.001	13.9 $\pm$ 0.2	1.3	0.000
M-9	1:2:20	0.5	18.8 $\pm$ 0.8	4.3	0.699	28.7 $\pm$ 2.6	9.1	0.061
M-10	1:3:20	0.5	11.7 $\pm$ 1.5	13.1	0.034	19.5 $\pm$ 1.6	8.1	0.002
M-11	1:2:25	0.5	15.8 $\pm$ 0.9	5.5	0.261	26.7 $\pm$ 1.1	3.9	0.003
M-12	1:3:25	0.5	7.7 $\pm$ 0.1	0.8	0.002	13.2 $\pm$ 0.2	1.6	0.000
M-13	1:2:50	0.5	15.2 $\pm$ 1.3	8.4	0.185	27.8 $\pm$ 1.4	4.9	0.008
M-14	1:3:50	0.5	11.8 $\pm$ 2.5	21.2	0.073	18.4 $\pm$ 1.4	7.6	0.001
M-15	1:2:100	0.5	33.5 $\pm$ 2.1	6.2	0.002	39.3 $\pm$ 1.1	2.9	0.003
M-16	1:3:100	0.5	35.6 $\pm$ 1.1	3.2	0.000	42.3 $\pm$ 0.1	0.3	0.000

**Fig. 10 - The impact of bottle waste glass replacement ratios on the compressive strength at 28 days of various mixtures.**

This statistical analysis indicates that the mechanical performance of cement mortar made from waste bottle glass is significantly impacted by the waste bottle glass replacement ratio, with some replacement ratios yielding variations within the experimental margin of error, while others demonstrate statistically significant improvements.

The 28-day compressive strength results showed that mixes containing both low and full replacement ratios of waste bottle glass (M-5, M-7, and M-15 in the 1:2 mixes group and M-16 in the 1:3 mixes group) either achieved or exceeded the minimum compressive strength required by Iraqi specification IQS No.5/2019 for structural mortar. These mixes might be used in circumstances with low external exposure effects. While other different mixes with varying replacement ratios influenced the strength behavior in a significant manner, which means they may be used for non-structural or architectural uses. In order to use it in the field, you would need to make sure it satisfies the requirements for dimensional stability and test its durability in the local environment, including exposure to sulfate, temperature variations, and moisture cycles. Additionally, it's crucial to consider the potential for an alkali-silica reaction at higher levels before using a lot of waste glass. This can be done through laboratory and pilot-scale field testing. These findings highlight how crucial it is to match national construction standards with laboratory results in order to guarantee durability and safety in practical applications.

3.3 Tensile strength

The tensile strength is defined as the stress calculated at maximum load. ASTM C 307 provides the following method for determining it, as depicted in Equation 1:

$$S = \frac{P}{bd} \quad (1)$$

Table 9 and Fig. 11 present the tensile strength results and statistical analysis values for all of the mixes, as well as the correlation of it to the groups mixed that were used in the study.

Table 9: Tensile strength test results and statistical analysis for all the mixtures

No.	C (cement): S (sand): G (waste glass) %	Tensile strength (MPa) Mean ± sd (n=3)	Coefficient of Variants (%)	Tensile strength p- value vs. Control mix at $\alpha = 0.05$
M-1	1:2:0	2.8 ±0.4	12.8	-
M-2	1:3:0	1.9 ±0.2	9.8	-
M-3	1:2:5	1.6 ±0.1	4.5	0.005
M-4	1:3:5	0.8 ±0.1	7.5	0.001
M-5	1:2:10	1.7 ±0.0	2.8	0.006
M-6	1:3:10	0.9 ±0.1	10.3	0.001
M-7	1:2:15	1.6 ±0.2	11.2	0.007
M-8	1:3:15	0.9 ±0.0	4.3	0.001
M-9	1:2:20	1.2 ±0.2	12.8	0.002
M-10	1:3:20	0.8 ±0.0	4.6	0.001
M-11	1:2:25	1.5 ±0.0	3.1	0.003
M-12	1:3:25	1.7 ±0.2	9.0	0.294
M-13	1:2:50	2.0 ±0.1	5.7	0.026
M-14	1:3:50	1.4 ±0.3	20.6	0.065
M-15	1:2:100	4.0 ±0.0	0.8	0.004
M-16	1:3:100	2.1 ±0.4	21.0	0.509

Fig. 11 error bars demonstrated the (±) standard deviation (SD) for samples in each mix. Tensile strength results for mixes M-3, M-5, M-7, M-9, M-11, and M-13 decreased by 42.857%, 39.285%, 42.857%, 57.142%, 46.428%, 28.571%, and

15.757%, respectively, when compared to the control mix M-1. Tensile strength decreased by 57.894%, 52.631%, 52.631%, 57.142%, 57.894%, 10.526%, and 26.315%, respectively, for mix M-2 as a control mix for various ratio mixes, M-4, M-6, M-8, M-10, M-12, and M-14, as compared to reference M-2. The results above indicate that at low glass contents (especially 10%), tensile strength increased in the 1:2 group, indicating that a fine and well-graded glass particle distribution contributed to better packing density and internal cohesion. Conversely, mixes with 25% and 50% replacement exhibited appreciable decreases, suggesting weak interaction between the hybrid sand-glass matrix and irregular grain packing. Notably, the 100% replacement (M-15) illustrated the strongest tensile strength in this group, an interesting note. This may be the result of a strong cement-glass bond and homogeneous particle types upon total removal of sand. On most replacement levels, the 1:3 group showed a more marked reduction in tensile strength. Reduced cement content and poor distribution of active bonding sites are probably the causes of this trend since they result in insufficient cohesion in the mix. These findings demonstrate that, with suitable mix compositions, recycled waste bottle glass can be used to increase the tensile strength of cement mortars. Finally, the results highlight the need for matching particle size distribution between waste bottle glass and natural sand.

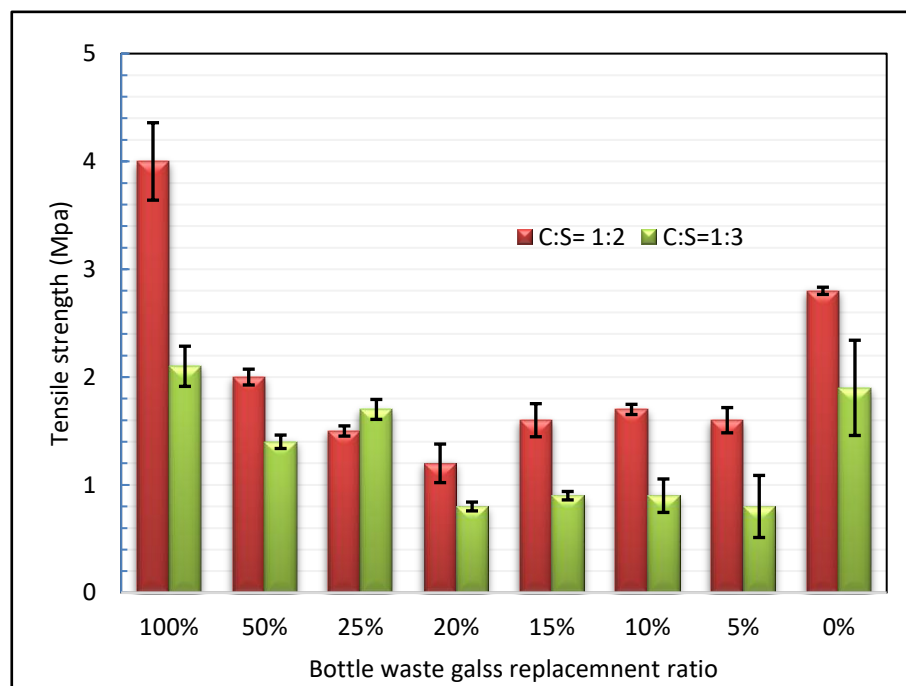


Fig. 11- The effect of bottle waste glass replacement ratios on the tensile strength of various mixtures.

An independent t-test with a significance level of $\alpha = 0.05$ was used to statistically evaluate the tensile strength results. M-1 and M-2 were used as the reference mixes for odd- and even-numbered mixes, respectively, as presented in table 10. The study found that most of the mixes, such as M-3, M-4, M-5, M-6, M-7, M-8, M-9, M-10, M-11, M-13, and M-15, had statistically significant differences ($p < 0.05$) from their controls. This means that even a small amount of waste bottle glass instead of natural sand can have a big effect on tensile strength.

On the other hand, mixes M-12, M-14, and M-16 had p-values of 0.05, which means that there was no statistically significant difference between them and their controls. This means that the differences in tensile strength for these mixes could have been caused by normal experimental variability.

3.4 Flexural strength

The results of flexural strength at 7 and 28 days are presented in Table 10. Pairwise t-tests were used to statistically compare the flexural strength results at 7 and 28 days, using the control mixes (M-1 for mixes with a 1:2 ratio and M-2 for mixes with a 1:3 ratio) as a reference. We set the significance level at $\alpha = 0.05$. If P is less than 0.05, the differences between the mix and the control mix are statistically significant. This means that adding waste glass in these amounts had a measurable effect on flexural performance. On the other hand, $P > 0.05$ means that there is no statistically significant difference compared to the control. This means that differences in strength may be due to normal experimental scatter rather than the effect of

replacing waste glass. At 7 days, several mixes (e.g., M-3, M-4, M-8, M-15, and M-16) showed highly significant improvements ($P < 0.001$) compared to the control, highlighting the strong early-age influence of waste glass at certain replacement levels. While, at age 28 days, particularly those with a moderate to high waste bottle glass replacement ratio, a broader set of mixes demonstrated statistical significance. This confirms the sustained or even enhanced flexural performance over time.

Flexural strength for M-3, M-5, M-7, M-9, M-11, M-13, and M-15 at 28 days improved by 88.732%, 33.802%, 14.084%, 35.211%, 25.352%, 25.352%, and 64.788%, respectively, when compared to the reference M-1. Also, flexural strength at 7 days for these groups showed a slight improvement compared to M-1. Flexural strength at 28 days increased by 25.000%, 25.000%, 6.667%, and 65.000%, respectively, for M-2 as a reference mix for different mix ratios, M-4, M-6, M-10, and M-14, as compared to reference M-2. The flexural stress improvement is considerable, indicating the uniform distribution of finely crushed waste glass particles, which enhanced mortar density by minimizing voids in the mix, resulting in improved stress distribution. In contrast, for M-8, M-12, and M-14, flexural strength decreased by 28.333%, 30.000%, and 3.333%, respectively, compared with M-2 at 28 days. The result demonstrated in Fig. 12 indicates that the C:S (1:2) mix consistently outperformed the C:S (1:3) mix at all replacement ratios. This may be due to the higher cement ratio, which improves bonding properties and mechanical characteristics. The optimum value of flexural strength is obtained at a 5% replacement ratio in the C:S (1:2) mix, indicating that the small quantity of bottle waste glass increases flexural strength, perhaps due to the favorable granular gradation. The 1:3 mix resulted in lower values; however, it reached an acceptable level of 10% and 5% substitution. Flexural strength was influenced at a high replacement level with different ratios (100% and 50%), displaying a complete or near-complete effect. This might be due to an abnormal distribution of the glass particles, and the variation in flexural strength might be due to insufficient support among cementitious components. In contrast, utilizing a moderate waste bottle glass ratio, such as 20% and 25%, can obtain effective performance, particularly in the C:S (1:2) group mix, which makes them potential candidates for novel mixtures with enhanced high mechanical properties. Overall, the findings indicate that utilizing waste bottle glass at a range of ratios (5% to 20%) can improve flexural strength, particularly in mix group C:S (1:2).

Table 10: Flexural strength test results for all the mixtures

No.	C (Cement): S (Sand): G (Waste glass) %	flexural strength at 7 days (MPa)	Coefficient of variants (%)	Flexural strength (7 days) P-value vs. control mix at $\alpha = 0.05$	Flexural strength at 28 days (MPa)	Coefficient of variants (%)	Flexural strength (28 days) P-value vs. control mix at $\alpha = 0.05$
M-1	1:2:0	5.2 $\pm$ 0.1	1.3	-	7.1 $\pm$ 0.0	0.5	-
M-2	1:3:0	3.8 $\pm$ 0.0	0.8	-	6.0 $\pm$ 0.1	2.1	-
M-3	1:2:5	9.4 $\pm$ 0.1	4.3	0.000	13.4 $\pm$ 0.3	2.1	0.000
M-4	1:3:5	5.3 $\pm$ 0.2	4.7	0.000	7.5 $\pm$ 0.5	6.0	0.006
M-5	1:2:10	5.3 $\pm$ 0.1	2.4	0.341	9.5 $\pm$ 0.3	2.6	0.000
M-6	1:3:10	3.9 $\pm$ 0.1	2.6	0.204	7.5 $\pm$ 0.2	2.6	0.000
M-7	1:2:15	5.7 $\pm$ 0.2	4.3	0.029	8.1 $\pm$ 0.2	2.7	0.002
M-8	1:3:15	2.3 $\pm$ 0.1	4.5	0.000	4.3 $\pm$ 0.3	5.8	0.001
M-9	1:2:20	5.9 $\pm$ 0.3	4.4	0.008	9.6 $\pm$ 0.5	5.1	0.001
M-10	1:3:20	3.8 $\pm$ 0.1	1.5	0.294	6.4 $\pm$ 0.5	8.4	0.278
M-11	1:2:25	6.4 $\pm$ 0.1	1.8	0.000	8.9 $\pm$ 0.2	2.4	0.000
M-12	1:3:25	2.5 $\pm$ 0.3	10.8	0.001	4.2 $\pm$ 0.4	10.6	0.002
M-13	1:2:50	5.4 $\pm$ 0.4	7.9	0.351	8.9 $\pm$ 0.3	3.3	0.000
M-14	1:3:50	3.2 $\pm$ 0.2	4.8	0.003	5.8 $\pm$ 0.3	5.5	0.312
M-15	1:2:100	9.0 $\pm$ 0.3	3.1	0.000	11.7 $\pm$ 0.2	1.8	0.000
M-16	1:3:100	7.8 $\pm$ 0.3	3.9	0.000	9.9 $\pm$ 0.3	3.4	0.000

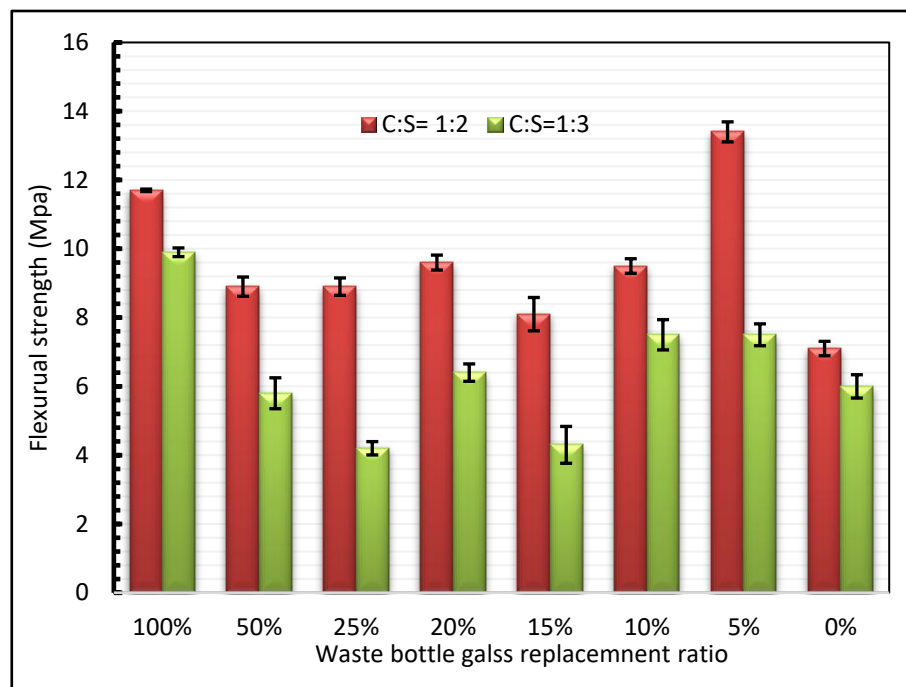
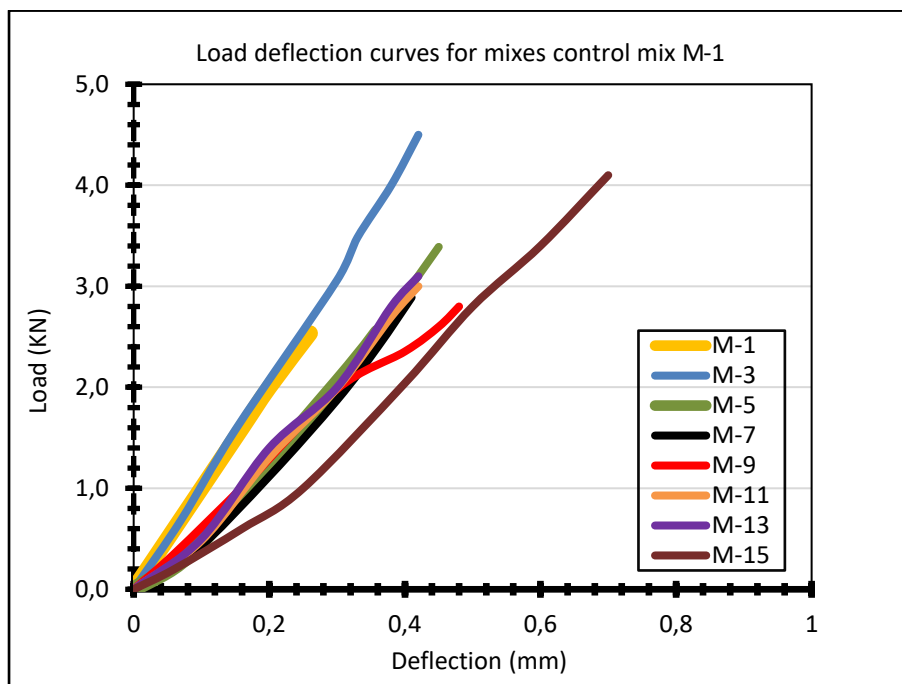


Fig. 12- The influence of bottle waste glass replacement ratios on the flexural strength of various mixtures.

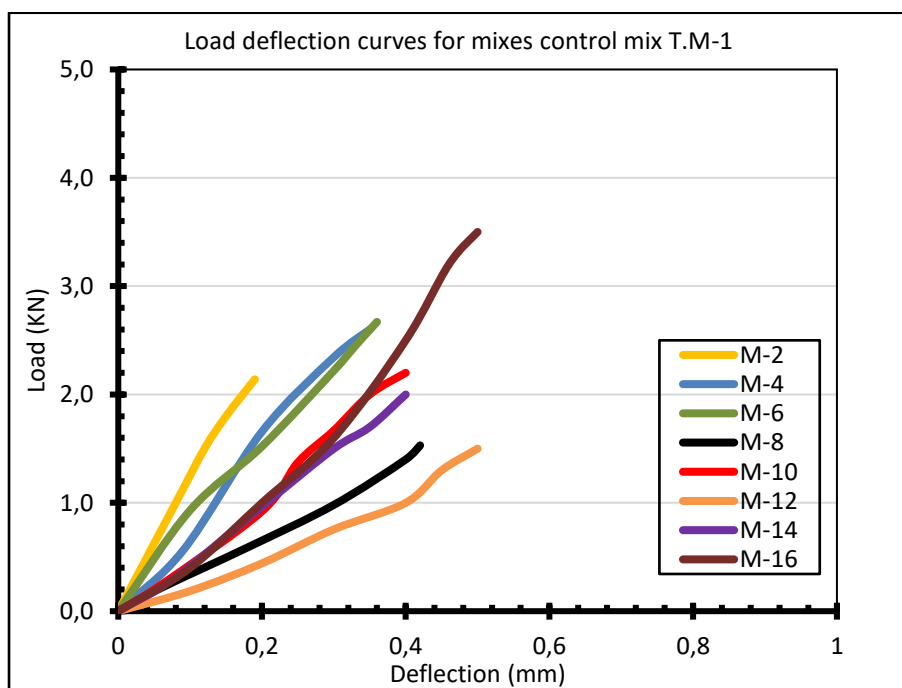
3.5 Load-deflection curves

Fig. 13 shows the load-deflection curves for each mix. The reference mix M-1 in the 1:2 (c: s) group (fig. 13(a)) exhibited a linear load increase followed by a sudden drop, indicating brittle failure with limited ductility. In contrast, M-5 and M-7 showed better deflection values and peak loads, reflecting increased ductile behavior. Control mix (M-1) exhibits a nearly linear behavior up to the peak, followed by a sharp fracture, indicating brittle behavior, low displacement at maximum load, and low ductility. The load deflection curves for M-3 through M-7 demonstrated a clear improvement in maximum load values, and a gradual increase in displacement is evident, particularly at M-5 and M-7. The curves began to bend gradually, indicating a more ductile behavior compared to M-1. While curves for M-9 to M-15 depict that after reaching maximum load, the displacement begins to decrease gradually, and the curve declines sharply. The curve steepens after the peak, indicating a return to brittle behavior. This is likely because excessive glass reduces adhesion to the cement paste, resulting in weaker internal bonding. This is attributed to the fact that the glass content in these mixtures acts as a filler, reducing porosity and enhancing internal cohesion at moderate proportions.

Fig. 13(b) represents mixture M-2 as a control mix and M-4, M-6, M-8, M-10, M-12, M-14, and M-16 with different glass proportions but at a higher sand ratio (1:3), i.e., a weaker and less viscous cement paste. The reference (M-2) displayed its brittle performance, as evidenced in the curve (short curve, sharp peak, and sudden collapse). This is expected from a mixture with a higher sand ratio (1:3), which reduces flexural strength. The load deflection curves for M-4 through M-8 indicated a significantly improved maximum load and displacement, especially at M-6 and M-8. The more curved and widened curves indicate greater ductility and better flexural resistance. In these cases, the glass helped compensate for the paste's weakness caused by the lack of cement, acting as both a filler and a stress dissipator. In contrast, the load deflection curves for M-10 to M-16 demonstrated that properties begin to decline; some blends (such as M-10) still perform better than the reference. Overall, there is a notable decline in performance after the peak, indicating decreased ductility and increased brittleness at higher waste bottle glass replacement.



(a) The load deflection curves for the various mixes are compared to those of the control mix M-1.



(b) Load deflection curves for mixes compared to the control mix M-2.

Fig. 13 - Load deflection curves for all mixes.

3.6 Flexural modulus

A material's flexural modulus is a mechanical parameter to be used to assess its degree of stiffness or resistance to bending. The results of flexural modulus for all mixes are depicted in Fig. 14. A higher flexural modulus means that the material is stiffer at first (the slope of the load–deflection curve is steeper in the elastic region) and that it bends less under the same loads, which means it is less ductile.

For the first group of 1:2 mixes at 0% replacement ratio, the control mix flexural modulus value was roughly 1232.7 MPa. At a low waste bottle glass replacement ratio, the modulus increased and peaked at 5% (1523.9 MPa), which is about 24% greater than the control mix. At 10% replacement, flexural modulus was still greater than the control (1343.3 MPa). After that, it is gradually dropped where its values are at 15% = 1185.3 MPa, 20% = 948.2 MPa, 25% = 935.7 MPa, 50% = 888.9 MPa, and 100% = 694.2 MPa. The microfiller effect and improved particle packing at low replacement ratio are reflected in this pattern, decreasing porosity to increase stiffness. The smooth and angular shape and size of the glass particles from waste bottles, especially at larger proportion ratios (>15%), result in poor mortar bonds and lower effective load transfer. This process makes the material less stiff and more ductile. This behavior is similar to the results found by Małek (2020) [17], Chen (2022) [14], and Çelik (2022) [21], who found that while higher levels of waste glass in strength properties are due to the interfacial transition zone, lower or optimal replacement ratios improved stiffness.

Furthermore, for the second group (1:3) mixes, the value of flexural modulus of the reference mix was 1128.4 MPa, with a peak value reached at a 10% replacement ratio of 1415.8 MPa, which was about 25% higher than the control mix for this group. There was also a second peak value reached at a 5% replacement ratio of 1340.7 MPa. Flexural modulus values were dropping down at 20–25% replacement ratio, 1066.4 MPa and 800.4 MPa, respectively; however, they went upwards at 100% replacement (1232.1 MPa), which was higher than the control.

This means that in cement mixes that are less cement-quantity dense, the best improvement develops at about 10% because of how the particles pack together and how the fillers function. The 100% increase could be because the granular matrix is more consistent when all the sand is replaced with well-graded waste bottle glass. This might render the material stiffer, but this effect depends considerably on the shape and size of the glass particles.

From the data that are discussed above, the higher values of flexural modulus were noticed in the (C:S = 1:2) mixtures group, indicating the better mechanical performance as the cement content increases. As previously discussed, the trial mixes that contain a higher cement ratio (C:S = 1:2) exhibit better ductile behavior and flexural modulus than other grouped mixes with a C:S = 1:3, emphasizing the importance of selecting the optimal percentage ratio to achieve high structural performance in mixes containing sustainable or alternative materials. These results are in agreement with earlier research on waste glass as a fine aggregate, which revealed that stiffness performance is determined by the state of balance between interfacial bonding and filler-induced densification.

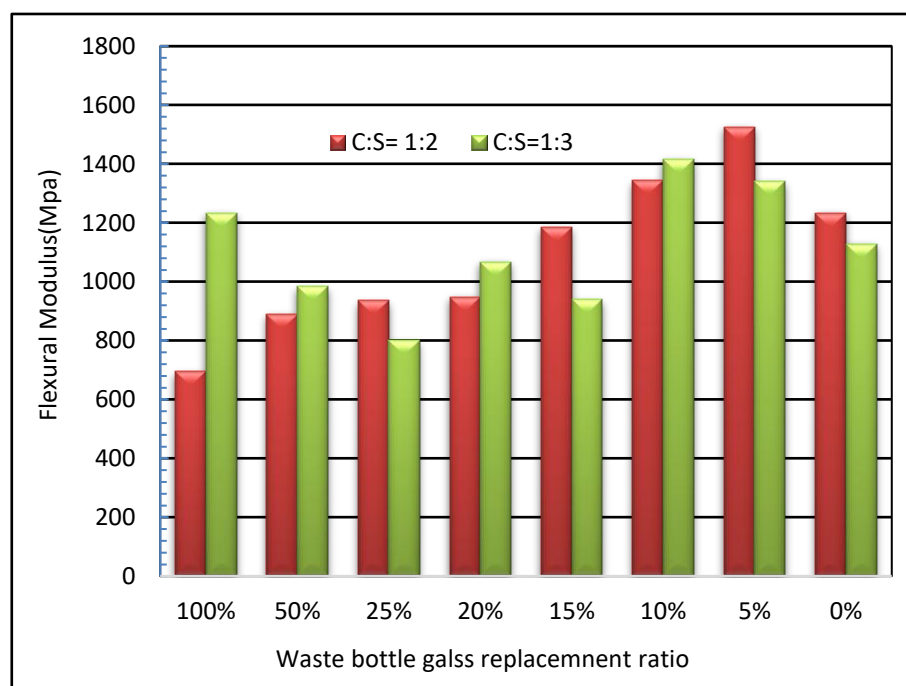


Fig. 14 - The influence of bottle waste glass replacement ratios on the flexural modulus strength of various mixtures.

3.7 Cost-effectiveness and economic effectiveness

Replacing natural sand with waste bottle glass in cement mortar indicates a beneficial and cost-effective alternative from an economic assessment. The average cost of 8 m³ of natural sand in Iraq ranges between 70,000 and 100,000 IQD (approximately 50 to 71 USD), or roughly 6.25 to 8.9 USD per m³. In contrast, we can obtain waste glass at very low cost from municipal or commercial waste sources. However, grinding and processing the waste bottle glass to the required particle size adds a reasonable cost of approximately 3–4 USD per m³, depending on energy consumption and equipment efficiency. Utilizing waste bottle glass as a partial or complete replacement for sand in mortar can reduce the cost per cubic meter of mortar by 15–35% due to lower raw material costs, especially at optimal ratios of 10–20%. Waste bottle glass recycling not only has effectiveness in immediately conserving raw materials, but in addition to this effect, it also reduces environmental waste management fees and eliminates the need for natural sand, thus addressing both economic and ecological issues. In some cases, especially for small-scale or large-scale construction projects, incorporating waste bottle glass offers a viable and cost-affordable solution.

3.8 Sustainability and Environmental Impact Indicators

In addition to the mechanical properties displayed in this study, there are measurable positive environmental impacts to using recycled waste bottle glass instead of natural sand. Partial or complete sand replacement reduces the effects of quarrying, cleaning, and transporting virgin aggregates while also redirecting solid waste from landfills, even when the cement content is maintained constant (and thus the dominant CO₂ source stays unchanged).

The estimated environmental benefits of using recycled waste glass as a substitute for natural sand in 1 m³ of mortar are summarized in Table 11. According to the findings, increasing glass replacement levels proportionately reduces the demand for virgin sand, keeping large amounts of waste glass out of landfills and reducing carbon dioxide emissions related to the extraction and processing of sand (emission factor ≈ 0.005 kg CO₂/kg). Hammond & Jones (2008) used the ICE database from the University of Bath to find the emission factor for natural sand (aggregate) [39]. The database says that each kilogram of sand releases about 0.005 kg of CO₂ (see embodied carbon entries for aggregates). This conservative number is what we utilized when calculating out how much good it could accomplish for the environment. The reductions support the environmental significance of the proposed mixes and are in agreement with global sustainability goals.

Table 11. Estimated sustainable benefits of replacing sand with recycled waste bottle glass (mortar per 2200 kg/m³)

No.	C (Cement): S (Sand): G (Waste glass) %	Waste bottle glass mass (kg) diverted from landfill	Avoided CO ₂ emissions from sand supply (kg CO ₂)
M-1	1:2:0	0	0
M-2	1:3:0	0	0
M-3	1:2:5	63	0.31
M-4	1:3:5	73	0.37
M-5	1: 2:10	126	0.63
M-6	1:3:10	147	0.73
M-7	1:2:15	189	0.94
M-8	1:3:15	220	1.10
M-9	1: 2: 20	251	1.26
M-10	1:3:20	293	1.47
M-11	1:2:25	314	1.57
M-12	1:3:25	367	1.83
M-13	1:2:50	629	3.14
M-14	1:3:50	733	3.67
M-15	1: 2:100	1257	6.29
M-16	1:3:100	1467	7.33

4 Conclusions

This study describes a novel method for producing sustainable cement mortar by replacing natural sand with waste bottle glass. The main aims of the study are to evaluate the mechanical properties of cement mortar, identify the optimum glass-to-sand replacement ratio that is desired for the appropriate mortar properties, enhance environmental responsibility, reduce raw material dependency, and manage solid waste effectively. To satisfy these aims, analysis of 16 different mortar mixes incorporating waste glass at varying ratios (0%-100%) and two mix designs (C:S = 1:2 and 1:3) allows the following conclusions to be drawn:

- Workability improved significantly at low glass replacement ratios in 1:2 mixtures but declined considerably in 1:3 mixes, particularly at 5-25% replacement ratios, due to weak cohesion and excessive sand content.
- M-15 and M-16 (100% glass) mixes provided significantly greater compressive strength than the reference mixes, with increases of 19.090% and 40.531%, respectively, illustrating the beneficial effects of fine glass in enhancing density and eliminating pores.
- At a glass substitution ratio of 10–20% in a C:S (1:2) group mix, compressive strength remained adequate and near the reference, indicating that these ratios are appropriate for achieving an acceptable balance between performance and cost-effectiveness.
- Flexural strength and modulus increased considerably in nearly all of the C:S (1:2) group mixtures, particularly at replacement ratios of 5% (M-3) and 100% (M-15), indicating better bonding effect, stress distribution, and reduced cracking.
- Mixes with a 1:3 mix ratio performed substantially less well than the C:S (1:2) group in all features, due to greater voids and lower effective cement content.
- The entire outcome was mostly measured at 10-15% replacement ratios for C:S (1:2) group mixtures, where workability was well balanced against mechanical strength and ductility.
- Given the local market price of sand and the low processing cost of glass waste, economic analysis indicates that substituting recycled waste bottle glass for natural sand could save between 20 and 30 percent of costs. This helps to make such sustainable materials achievable for low- to medium-scale construction efforts.
- Based on this study, waste bottle glass—either partially or completely—if the proportions are suitably changed and bond-enhancing admixtures are applied, can be used to substitute natural sand in cement mortar. Together with a suitable mix design (particularly a 1:2 ratio) and modest substitution levels (10–15%), it presents a good road toward greener, high-performance, and resource-efficient building material.

5 Recommendations

Below is an overview of challenges on which additional investigation is recommended:

- Further investigation into the alkali-silica reaction (ASR) at a higher ratio of waste bottle glass is essential to ensure the long-term effect and durability action of mortar.
- Pozzolanic or fiber additives (such as fumed silica or fiberglass) should be explored to improve microstructural and internal bonding properties at high replacement ratios of waste bottle glass.
- It is recommended that a better ratio be applied realistically to practical structural elements to explore the chance of field achievement.
- Further studies are recommended to incorporate other properties such as shrinkage, permeability, and sulfate resistance to investigate mortar's long-term behavior.

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Competing interest's statement

The authors reveal that they have no conflicting interests.

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