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Effect of Glass Wastes on Basic Characteristics of Controlled Low-Strength Materials

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HIGHLIGHTS

- The ability to use recycled glass as a substitute to fly ash and sand.
- The effect of waste glass percentages on plasticity and the mechanical properties of controlled-low strength materials.
- The possibility of producing sustainable, controlled, low-strength materials of excavatable and structural flowable fill by using recycled fine and coarse recycled glass.

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ABSTRACT

The harnessing of glass waste, which is slow to decompose and has high recycling costs, is in the interest of supporting and stimulating a balanced construction pattern that is interdependent on the living environment. Consumable food and drink bottles are one of these forms of waste that can be calibrated to meet desired specifications. Controlled low-strength materials with low and deliberate strength for future excavation have highly desirable rheological properties, active hardening, and zero or rare separation of materials can be maintained with waste glass substitution. In this study, an experimental evaluation was commenced to estimate the practicality of waste glass (fine and coarse powder) by replacing fly ash and natural sand with it to control low-strength materials. A sum of seven slurry blends was intended by employing several ratios (10%, 30%, and 50%) of fine and coarser waste glass. Some characteristics of plasticity and hardness were observed, such as fine glass decreased flowability. In contrast, coarser glass decreased dramatically, exceeding the minimum limit of 20%, which necessitated the use of superplasticizer in a proportion that corresponds to the increase in the replacement. Unit weight slightly increased with fine glass substitution, but in the Coarser substitution, a steady decrease occurred. The compressive strength of 28 days in fine glass replacement is less than the reference mixture, but it exceeded it at 90 days. A mixture incorporating coarse waste glass was higher at 28 days and developed at 90 days.

1. Introduction

Controlled low-strength material (CLSM) is a mixture of cementitious material (Portland cement or fly ash type c), fly ash, soil or aggregates, water, and possibly chemical admixtures that generate a soil replacement material when the cementitious material is hydrated. Flowable fill, flow fill, controlled density fill, and soil-cement slurry are some of the other names for CLSM. CLSM is commonly utilized as pipe embedment and backfill in place of compacted backfill or inappropriate native soil [1]. It is a material with a compressive strength of no more than 8.3 MPa, and currently, the most common and used is with a resistance of no more than 2.1 MPa for possible future excavations [2]. These materials vary from low-strength concrete, although the underlying idea is similar to self-compacting concrete. As a result, these materials are often known as grout materials. It is used in various civil engineering projects, including backfilling and filling gaps where compaction is impossible, such as under-existing buildings and roads, filling abandoned constructions under the earth, and many more. In addition, controlled low-strength materials (CLSM) are more favorable than other materials in terms of labor and equipment requirements due to their flow properties [3].

The literature review shows that previous studies applied waste materials for producing CLSM. Wu et al. [4] evaluated the practicality and application of paper mill solid wastes into CLSM, wherein fly ash was used instead of cement, bottom ash was supplied as a substitute for fine aggregate, and paper sludge was utilized as a fibrous additive. The results show both fly ash and bottom ash may be used effectively to make CLSM mixes with the desired qualities. Le et al. [5] reported the suitability of

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ponded materials as backfill materials when employing air foam technology. The purpose of this study was to recycle as much ponded material as possible with a minimum amount of cement by utilizing air foam. Bassani et al. [6] investigated cement kiln dust and aggregates (natural sand of river with a gradation of 0/4 mm was utilized) to create novel CLSM. The results show how this mixed element affects the features of both plastic and hardened CLSMs and their limits. (Do and Kim [7] investigated the viability of using red mud as a partial substitute for Portland cement in a controlled low-strength material (CLSM) generated from ponded ash and fly ash. The results show that partial replacement of cement by red mud, up to 30 % in combinations, would impair flowability and slightly increase corrosively. In terms of strength at 28 days, the highest strength CLSM could be created by an ideal replacement of 15% red mud to cement. Azmi et al. [8] substituted waste paper sludge ash (WPSA) for cement and used recycled aggregate gathered from construction sites. The percentage levels of WPSA used are 10%, 20%, 30%, 40%, 50%, and 60%. The result shows that although the workability of mix design diminishes as WPSA content increases, it is adequate for flowable fill application based upon ACI guideline use. Solanki et al. [9] investigated whether reclaimed glass powder might be applied as fly ash (type c) replacement in CLSM. Results showed that Reclaimed glass has the potential to be an acceptable replacement for fly ash in CLSM based on flow thickness results and the compressive strength data. Xiao et al. [10] investigated the pozzolanic interaction among waste glass powder (GP) & hydrated lime (CH) in this work to produce cement-free CLSM. It was found that a high GP/CH ratio could improve the mixes' workability and self-compacting behavior. Also, all samples attained the requisite 28-day unconfined compressive strength for CLSM.

Although there is no accurate data on the amount of waste glass formed in Iraq, there is no doubt that its cumulative quantities. Abandoned solid waste has increased significantly due to the absence of or ineffective collection, treatment, and disposal systems for this waste which is slow to decompose and might persist for centuries [10][11]. When compared to other supplemental cementitious materials (SCMs), the present study's trend shows that waste glass may be regarded as a good building material due to its flexible size, form, chemical composition, and broad availability [12–14][12–14]. The current research work differs from the previous studies (with glass replacement) by the use of Fly Ash type F instead of type C and natural sand with a gradation that falls within the fourth area according to the Iraqi specification, and rough glass instead of sand at rates of 10% to 50%. In addition, the study uses ground glass instead of fly ash with the same ratios and studies its effect on plastic properties and in-service properties.

The research aims to examine the changes in the properties of the wet state in terms of flowability, unit weight, and hardened state of compressive resistance. This is done by replacing fly-ash with fine waste glass (less than 45 micrometers) and natural sand with coarser waste glass (less than 600 micrometers). The practical feasibility of this compensation is to achieve sustainability and reduce the costs of controlled low-strength materials (CLSM).

2. Materials

In this experiment, ordinary Portland cement with the brand name (MASS) from Suleimanyah, Iraq, was employed, which complies with Iraqi standards IQS No.5/2019 [15]. Tables 1 and 2 show its chemical composition and physical qualities.

Table 1: Chemical Oxide analysis

Oxide	%by weight	Limit of Iraq specification No. (5) _ 2019
silicate oxide	20.1	-
iron oxide	2.5	-
aluminum oxide	4.55	-
calcium oxide	62.1	-
magnesium oxide	2.75	< 5
Potassium Oxide	1.10	-
Sodium Oxide	0.10	-
Loss on ignition L O I	2.39	< 4.0
Sulfate oxide	2.22	< 2.8
Insoluble Residue I.R	1.24	<1.5
Lime Saturated Factor	0.94	0.66-1.02
	Main Compounds	
Tricalcium silicate(C_3S)	59.6	(Bogues equations)
Dicalcium silicate (C_2S)	19.24	
Tricalcium aluminate(C_3A)	7.83	
Tetracalcium (C_4AF)	9.6	

Table 2: Physical Properties of Cement (Type ONE)

Physical properties	Test result	Limit of Iraq Specification No. (5)2019
Setting time	-	-
Initial setting time, hrs.: min	2:25	≥ 1:00
Final setting time, hrs.: min	8:21	≤ 10 hrs.
Specific gravity	3.16	
Specific surface area cm²/g	3590	≥ 2300
Compressive strength	-	-
Two days MPa	17.8	≥ 10
28 days MPa	33	≥ 32.5

After sieving on a 600µm sieve, natural sand and desert origin were used as a fine aggregate. The aggregate grading and physical properties listed in Tables 3 and 4 are all in compliance with ASTMC778, 2017[16] (graded sand) as well as Iraqi standards IQS No.45/1984[17].

Table 3: Fine aggregate gradation

Sieve no. (µm)	% Passing through	Limits of the Iraqi Specification N0.45 zone 4	ASTMC778, 2017 Graded sand
1.18 (No. 16)	100	90-100	100
600 µm (No. 30)	100	80-100	96-100
425 µm (No. 40)	67	-	60-75
300 µm (No. 50)	23	15-50	16-30
150 µm (No. 100)	4	0-15	0-4

Fineness Modulus(F.M.) =2.06

Table 4: Fine sand properties used in this work

Physical properties	Test results	Limit of Iraqi specification No.45/1984
Specific gravity	2.6	-
Bulk density (kg/m^3)	1675	-
Absorption %	4.78	8
Sulfate content %	0.42	Specification requirements ≤ 0.5% max

Sika® ViscoCrete®-5930 L IQ is a polycarboxylate polymer technology (3rd Generation) high-range water-reducing and super plasticizing additive for concrete and mortar that fulfills ASTM C-494 [18] standards. It was utilized in this work to increase flow in coarse glass with high substitution ratios (> 20%), as shown in Table 5.

Table 5: Properties of Chemical Admixture (SP)

Composition	An aqueous solution of modified polycarboxylates
Specific gravity	1.085 ± (0.01) g/cm3
pH-Value	4 - 6
Total chloride ion content	Nil

The fly ash used in this study is produced by the "EUROBUILD FLY ASH" company, and it conforms to BS 3892 Part 1 and BS EN 450[19]. The chemical composition and the physical requirements of fly ash are shown in Table 6.

Table 6: Specification for pulverized-fuel ash to use Portland cement

Composition	Consist essentially of reactive silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), the remainder being iron (III) oxide (Fe_2O_3) and other oxides.
Sulfuric anhydride	The content of sulfuric anhydride, SO3, ≤2.0 %
Loss on ignition	The loss on ignition ≤7 %
Chloride	The chloride ion content ≤0.10 %
Calcium oxide	The calcium oxide content ≤10.0 %
Moisture content	The moisture content of the Pulverized-fuel ash (Pfa) ≤ 0.5 %
Fineness	The fineness of the Pfa expressed as the proportion by mass retained on a 45 µm test sieve ≤12.0 %
Particle density	The particle density of the Pfa ≤2000 kg/m^2

This work used two types of recycled waste glass (RWG), fine RWG and coarse RWG. RWG is manufactured from post-consumer container glass in both types, with the chemical composition shown in Table 7. The fine RWG, called FWG, is processed by a small mill into a powder that is pure and off-white in color Figure (1a), with a minimum fineness of effective diameter of a fine powder, is equal to (975.1 nm). The coarser RWG, or CWG, is a 0.150 to 0.60 µm powder with a minimum fineness of 98 percent Figure (1b).

Table 7: Physical& Chemical composition of recycled waste glass

Chemical content	Results
Silicon dioxide (SiO_2)	70
Aluminium oxide (Al_2O_3)	1.3
Iron(III) oxide (Fe_2O_2)	<1
calcium oxide (CaO)	11
magnesium oxide (MgO)	0.2
sulfate oxide (SO_3)	<0.5
nitrate oxide Na_2O	13
Loss on ignition (L.O.I.)	<0.1
Specific gravity	2.48

Figure 1: ground fine glass (a) and sieved coarse waste glass (b)

3. Methods

3.1 Mixture proportioning

In this study, slurry fill mixtures with different dosages of fly ash, FWG, and CWG powders were produced, and the ratio of each ingredient was chosen in advance. One reference combination was made with only conventional Portland cement (60 kg/m³), fly ash (178 kg/m³), fine aggregates (i.e., sand1390 kg/m³), and water (404 kg/m³) (no reused glass). To study the influence of the proportions of fine waste glass to coarse waste glass on slurry mix behavior. The remaining ten mixes were split into two groups (three mixes in each group) and prepared using FWG percentages of 10%, 30%, and 50% (percentages of substitution to fly ash), in addition to CWG percentages of 10%, 30%, and 50% (by weight of total sand of the same replacement percentages),as shown in Table 8.

Table 8: Details of Mixes

Mix name	Cement (gram)	Fly ash (gram)	weight of replacement (gram)	Sand (gram)	Water (milliliter)	W/ Supplementary Cementitious Materials ratio
Reference mixture	240	712	-	5560	1424	1.5
Fine waste glass substitution 10%	240	641	71	5560	1424	1.5
Fine waste glass substitution 30%	240	499	213	5560	1424	1.5
Fine waste glass substitution 50%	240	356	356	5560	1424	1.5
Coarse waste glass substitution 10%	240	712	560	5000	1424	1.5
Coarse waste glass substitution 30%	240	712	1668	3892	1424	1.5
Coarse waste glass substitution 50%	240	712	2780	2780	1424	1.5

3.2 Preparation of specimens

3.2.1 The mixing procedure

The method was carried out in compliance with the following guidelines (ASTM: C305-14) [20].

3.2.2 Casting and curing

This procedure of curing CLSM specimens is followed [ASTM C109/C109M − 16a10.5 (Storage of Test Specimens)] [21].

3.3 Testing of specimens

3.3.1 Flow consistency tes

The method was carried out in compliance with the following guidelines (ASTM: D6103-04) [22]. An open-ended cylinder is placed on a flat, level surface and filled with fresh CLSM. The cylinder is raised quickly so the CLSM will flow into a patty. The average diameter of the patty is determined and compared to established criteria, as shown in Figure 2.

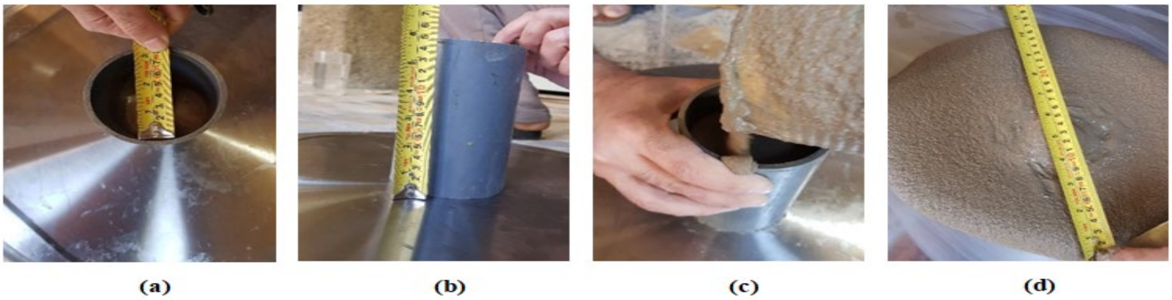

Figure 2: Cylinder dimensions (a, b) and filling it (c) and lifting then measuring the spreading diameter (d)

3.3.2 Density (unit weight)

This test procedure is immediately done after the mixing procedure followed by (ASTM: D6023−16) [23].

3.3.3 Compressive strength

CLSM cubes were prepared according to (ASTM C109/C109M − 16a) [20], computer-controlled electronic universal machine by Laree technology co., ltd was used for compression testing Figure 3. The cubes were tested immediately after being taken from water storage while they were still saturated and surface dry. The average of the compressive strengths of three cubes was recorded for each testing age.

Figure 3: Computer-controlled electronic universal machine by Laree technology co., ltd (a) and cubes specimen shape at failure (b, c)

4. Results and Discussion

4.1 Flow Consistency Test

Through Table 9 and Figure 4, it is clear that all the mixtures with substitution are less than the reference mixture. It is noted the significant decrease in the flowability of the mixtures containing recycled coarse glass Figure1, as the percentages (30,50%) are less than the minimum limit (According to ACI 229-13) [24]. This was corrected by using the super plasticizing add-on in the proportions shown in Table 8. This dramatic decrease is probably owing to the sharp and pointy shape of the glass grains beside natural sand. The irregular shape of the glass grains leads to an interlocking between the grains contiguous and thus less flow. This justification corresponds to [25]. As for the part replaced by the fine glass from the fly-ash in Figure 1, the decrease in flowability in line with the increase in the replacement percentage was slight, and it was able to maintain results close to the reference mixture. This decrease can be attributed to the fact that the glass is very fine, which has a high surface area/volume, and therefore its water adsorption is high. This statement is in line with [25].

Table 9: Flow ability results

Mix name	Flow spreading (mm)	Variation ratio (%)	SP by weight of BSCM (%)	Modified flow spreading (cm)
RM.	296	------	----	------
Fine waste glass substitution		**Group 1 Fly ash replacement**		
FWG10%	291	-1.6	----	------
FWG.30%	278	-6	----	------
FWG50%	261	-11.8	----	------
coarse waste glass substitution		**Group 2 Natural sand replacement**		
CWG10%	255	-13		
CWG30%	172*	-41	0.5	221
CWG50%	134*	-54.7	1	212

* Below flow minimum limit (200mm)

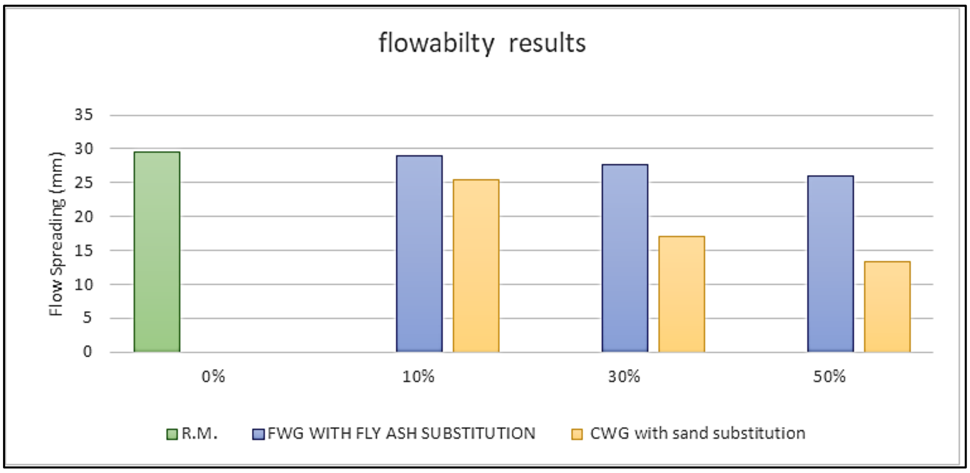

Figure 4: Effect of glass substitution percentage on flow spreading

4.2 Unit Weight (Wet Density)

As shown in Table 10 and Figure 5, the slight density increase is noted with an increase in the percentage of glass used instead of the fly ash, which reached less than 0.5% to a maximum of 50% substitution. This is because the specific weight of the glass (soda-lime) is 2.2, slightly higher than the specific weight of the fly-ash at 2.4. On the other hand, the results of the wet density of the mixtures replacing the recycled glass with sand, with a steady decrease from the reference mixture, increased with the increase in the replacement percentage and reached less than 1% at the highest percentage (50%). The small difference in density is that the specific gravity of the glass (soda-lime) is 2.48, which is close to the specific gravity of sand at 2.6.

Table 10: Unit weight test output

RM.(kg/m³)	**Group 1**			**Group 2**		
	Fine waste glass With fly ash substitute (kg/m³)			***Coarse waste glass with sand substitute (kg/m³)***		
1987	10% FWG 1988	30% FWG 1992	50%FWG 1996	10%CWG 1985	30%CWG 1979	50%CWG 1970

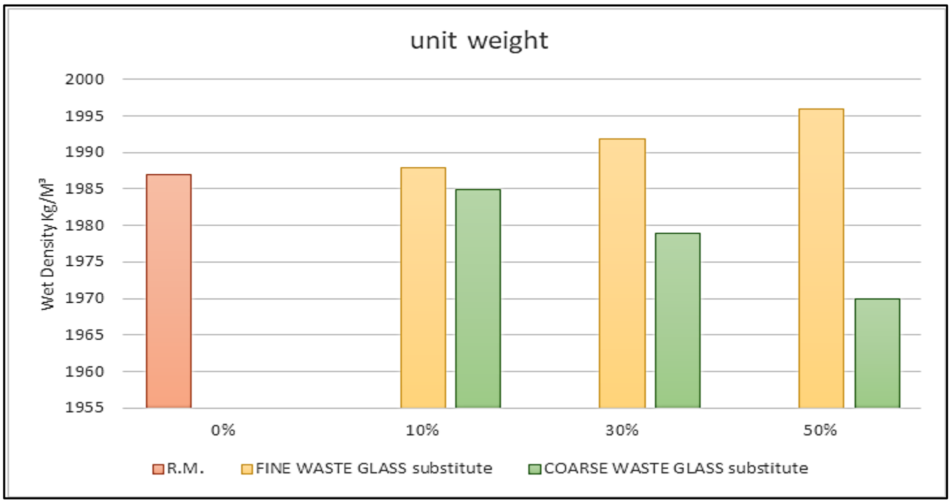

Figure 5: Effect of glass substitution percentages on unit weight

4.3 Compression strength test

The compressive strength test values are shown in Table 11 and Figure 6, which concern the replacement of glass powder with fly-ash. The results for the age of 28 days were decreased by - 0.7%, -5.1%, and -11.1% to the substitution percent (10% to 50%) respectfully, relative to the reference mixture, which was 1.35 MPa, and this contradicts what was [9] stated (for 28 days increment compared to the reference mix). And perhaps, the reason is due to the effect of the type of fly ash used (type F) instead of (type C) for the mentioned researcher, as the content of Portlandite is less than it is known, and this affects the effectiveness of secondary tobermorite formation. Also, these results were contrary to what was stated in the researcher's review, which touched on a lot of research that supported his position.

As for the results for the age of 90 days, there was a significant increase in line with the increase in the compensated ratio from (10% to 50%): 3.7%, 22%, and 55%, respectively, relative to the control mixture, which was 1.8 MPa. This phenomenon was consistent with other researchers, such as [26, 27], who attributed the reason to the slow reaction rate of the replaced glass powder, which led to a slight delay in the early ages. With the length of the curing period, the amorphous silica slowly dissolves in the alkaline environment and reacts with calcium oxide to form hydrated calcium silicate. Therefore, the increase in the later ages results from a compact microstructure in the interfacial transition region of the paste system. Furthermore, according to the researcher [9], the surface imaging method (SEM) reveals that the glass particles are smaller than the fly ash particles. This characteristic helps in an improved Pozzolanic reaction compared to the fly ash.

Table 11: Compression test outputs

Mix description	**Compressive strength (MPa)**	
	28 days	***90 days***
RM.	1.35	1.8
	Fly ash replacement with fine waste glass	
FWG10%	1.34	1.84
FWG30%	1.28	2.2
FWG50%	1.2	2.8
	Sand replacement with coarser waste glass	
CWG10%	1.7	1.82
CWG30%	3.2	3.5
CWG50%	4	4.04

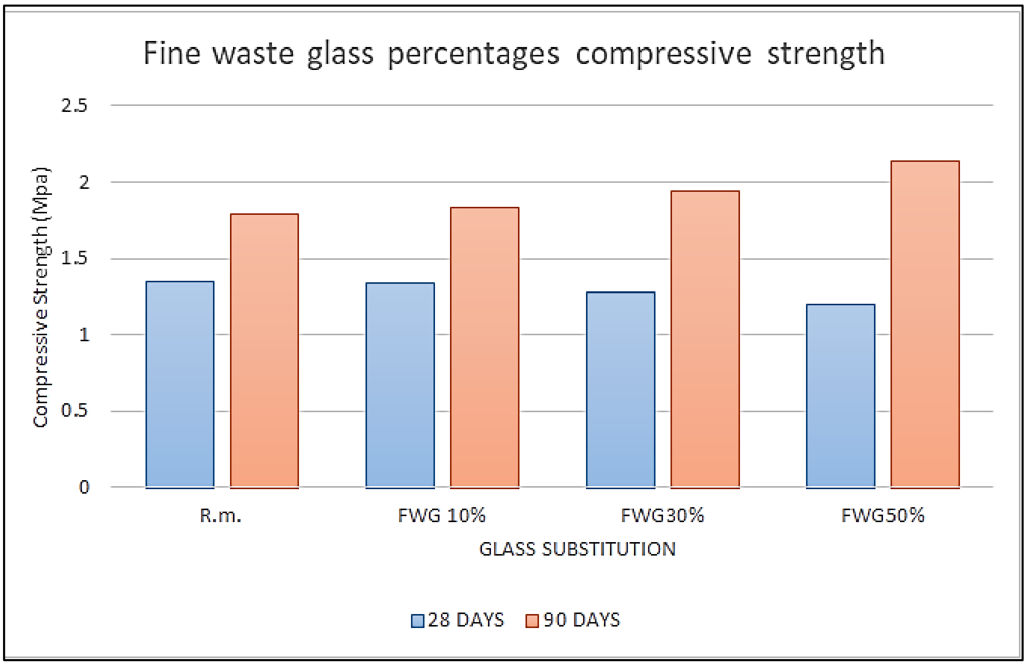

Figure 6: Effect of fine glass percentages on compressive strength at 28, 90 days of curing

As for the replacement of the rough glass with sand, Table 11 and Figure 7 shows the nature of the results. The compressing strength values at 28 days for all the addition ratios (10%, 30%, 50%) were higher than the reference mixture: 25.9%, 137%, and 196.29%, respectively. This increase is consistent with [28, 29] to some limit.

The increase that occurred in general (28 and 90 days) and for the proportions of 10% in specific is mostly due to the sharp angular nature of the glass aggregate, which has a larger surface area than the normally rounded grains of sand. Therefore, its specific gravity is less than sand. Still, it has a hardness coefficient that may exceed sand. It is believed that the pozzolanic reaction for the used granular size is (600) microns to (150) microns. This size is in the range of 70 to 74 % of what Shi et al. [30] determined about particle size distribution effect on strength activity index. It may act as a filler for voids that are more visible in conventional sand. At the same time, the extreme increase of proportions is 30% to 50% of it is possible that the superplasticizer had a great role in this rise through the uniform distribution of the particles of the binder and providing the appropriate space for the occurrence of uniform chemical bonding [31].

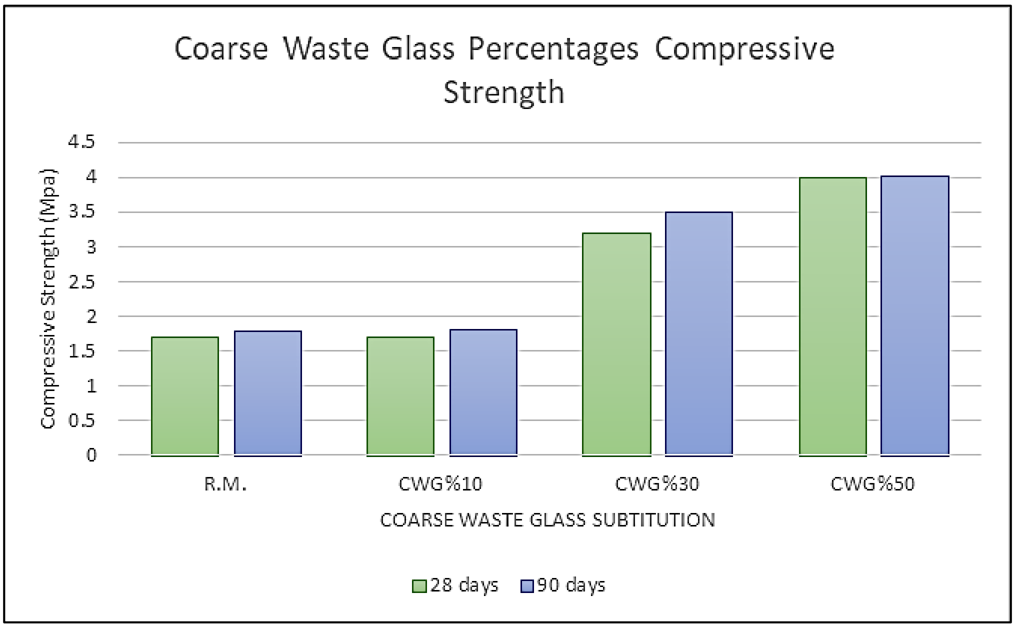

Figure 7: Effect of coarse glass replacement on compressive strength at 28, 90 days

Concerning the increase of 90 days age, the compressive strength rate between 28 and 90 days decreased with the increase in the replacement rate until it reached 50%, where it is observed to be almost equal for the age of 28 and 90 days, where the percentage of increase was 33%, 7%, 9.3%, 1% for the replacement rates 0, 10, 30, 50 by order. This behavior is somewhat consistent with [32], who assumed that the Portlandite content decreased rapidly and by increasing the alkali present in the glass, which amounted (to 13%) required for the formation of hydrated calcium silicate or (C-A-S-H) at an early age. In addition to its depletion, the alkali may begin to interact with the active silica in the glass, negatively affecting the development of strength at later ages.

5. Conclusion

Below are points that summarize the study, conclusions, and suggestions for the future period:

- The flow rate decreases steadily with the increase of the compensation ratio for both types of glass. However, in the rough type, it drops below the permissible limit (200 mm) at 30%, which requires a superplasticizer to maintain the requirements of ACI.
- The wet unit weight results were above the minimum acceptable level (1840kg/m^3), depending mainly on the specific gravity of the substituted ingredients as it increased and vice versa.
- The strength of the 28-day life of mixtures compensated with fine glass is lower than that of the reference mixture due to the slowness of the pozzolanic reaction, but it is higher at 90 days. As for the compressive strength of blenders compensated with rough glass, it was higher than that of the reference mixture for the age of 28, and at the replacement ratio of 30%, it was higher than 2.1 MPa (Excavatability lifespan exceed) and also 90 days due to the dependence of resistance on mechanical interconnection.

CLSM's use of refuse materials and/or manufacturing by-products has many prospects for future sustainable maturing. In search of this quest, below are some of the suggestions that can contribute in this area:

- The possibility of conducting future studies on adding colored glass and studying the effects.
- Evaluate the Performance of long-term curing and durability tests such as alkali-silica reaction (ASR), sulfate attack resistance, etc.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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