Open Journal of Civil Engineering, 2023, 13, 252-262
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Experimental Study of the Physical and Mechanical Behaviour of Mortar Formulations with Fine Sands of Recycled Glass

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How to cite this paper: Kplolanyo, A.D., Ouro-Djobo, S.E., Bollanigni, A.K., Assogba, K.K. and Sonnou, T. (2023) Experimental Study of the Physical and Mechanical Behaviour of Mortar Formulations with Fine Sands of Recycled Glass. *Open Journal of Civil Engineering*, **13**, 252-262.
https://doi.org/10.4236/ojce.2023.132019

Received: May 16, 2023
Accepted: June 5, 2023
Published: June 8, 2023

Abstract

This work is part of an experimental contribution approach to the study of the incorporation of glass sand from the grinding of recycled glass waste in cement mortars and its influence on the physical and mechanical behavior of semi-rich mortars without adjuvants. For this purpose, after a physical characterization of the sands, eight (08) formulations of mortars based on cement CEM II B/L 32.5R and fine sands (0/2) of glass at mass contents of 0%, 10%, 20%, 30%, 40%, 50%, 75% and 100% of the silty sand (0/2) were made respectively to three (03) types of fine glass sand (white, brown, green) with water dosages on cement (W/C) of 0.50, 0.45, 0.40. The results obtained show that the fine sands of recycled glass have a higher water absorption than the silty sand and the physical properties of the mortars prepared are affected by the increase in the glass content. The mechanical performances are obtained for the ratio W/C = 0.50 and the formulation of glass mortars for an optimal compressive strength superior to glass-free mortar requires a substitution of 10% for fine white glass sand, 20% for sand fine green glass and 75% for fine brown glass sand. The comparative study between these different compositions of fine glass sand mortars shows that the mechanical performances of fine brown glass sand are better than other glass sands but generally remain inferior to the control mortar based on natural silty sand.

Keywords

Glass Waste, Glass Sand, Mortar, Compression Strength, Bending Strength, Absorption Rate

1. Introduction

Recycling of waste in construction is an essential contribution to the protection of the environment and the promotion of sustainable development in our modern societies. It not only contributes to improving sanitation conditions of cities and the waste management cycle, but also to improving certain physical and mechanical properties of construction materials. This is the case of building waste (bricks, concrete) that is recycled to replace or substitute aggregates in new construction projects or in specific works at reduced costs [1]. The waste of broken glass bottles from households is an integral part of this non-biodegradable solid waste which is also recovered in construction by incorporation in mortars and concretes because of their origin resulting from the high temperature fusion of silica sand. Successfully formulation of mortars and concretes from these recycled waste aggregates will make it possible to obtain more economical structures. Thus, the use of recycled aggregates from demolition and industrial waste makes it possible to formulate concretes that are less expensive and have improved properties [1] [2].

In Togo, environmental studies revealed in 2011 that the situation of recoverable glass waste in the city of Lomé is eight (8) tons per day in the dry season and three (3) to five (5) tons per day in wet season with an average of about two thousand (2000) tons per year [3]. This glass waste is either reused in households or crushed and recovered for use as fine and coarse aggregates in mortars for plastering the exterior walls of residential buildings, in the manufacture of self-locking paving stones and works of art. Glass powder residue from crushing and grinding is not used because of the swelling and cracking it causes in mortars and concretes [4].

However, previous studies on the recovery of mixed glass aggregates have shown that the formulation of mortars with crushed glass waste in the state of coarse glass sand (0/5) and with a dosage W/C = 0.43 improves the compressive strength of mortars when they are substituted up to 30% of the sand portion [5]. What about fine glass sands (0/2) that will make it possible to obtain mortars and concretes whose glass crystals will not be visible to the naked eye?

Therefore, this experimental study aims to find a mortar formulation based on silty sand substituted for fine glass sand in order to contribute to the study of the incorporation of glass aggregates in mortars and to the protection of the environment through large-scale use of glass waste. Thus, following the characterization of silty sand and three types of glass sands from white glass waste, brown and green, the study of the physical and mechanical behaviour was carried out on various mixtures of mortars elaborated by substituting the silty sand by the glass sands for mass percentages of 10%, 20%, 30%, 40%, 50%, 75% and 100% with ratios of water to cement (E/C) 0.50, 0.45 and 0.40. This will allow us to analyze the influence of the color of fine glass sands 0/2 on cement mortars and determine the best type of glass to use as fine sand with a particle size of 0/2.

2. Materials and Methods

2.1. Glass Sands and Silty Sands

The glass sands used (**Figure 1**) are obtained by fine grinding the waste of white, brown and green glass bottles recovered from households. The process for obtaining glass sands is identical to that of the work of Apedjinou *et al.* [6]. The physical characteristics of the glass sands are presented in **Table 1** and the particle size distributions in **Figure 2**.

The sand used is a silty sand available locally in the canton of Gounokope in the prefecture of the lakes of Togo. It is a fine sand with a tight particle size that which is part of the specification spindles of the silty sands of south Togo developed by Amey [7]. The sample was taken from the quarry being mined and the particle size curve obtained is shown in **Figure 2**. Its main physical characteristics are grouped together in **Table 1**.

2.2. Cement

The cement used for this study is CEM II B/L 32.5R or SUPERCPJ45 compound cement from the CIMTOGO cement plant in Lomé. It complies with NF P 15-301 and has an apparent density is 0.97 with an estimated 28th day compressive strength of 32.5 MPa. It is composed of 16.33% SiO_2 and 58.80% CaO [6].

2.3. Mixing Water

The mixing water used is drinking water that comes from the Togolese water company (TDE) of Togo. It is not stored but used directly for the production of different mortar formulations.

2.4. Experimental Procedures and Mortar Formulations

The preparation of the mortar specimens was carried out in accordance with NF EN196-1, September 2016 for the cement tests for the determination of mechanical resistance [8].

After a physical characterization of the materials used in the formulation of glass and glass-free mortars, the mortars were developed by substituting the silty sand by the glass sands for 10% mass percentages, 20%, 30%, 40%, 50%, 75% and 100% with water to cement ratios (E/C) of 0.50, 0.45 and 0.40. **Table 2** shows the mass composition of the mixtures studied for each type of glass sand.

The preparations of the various formulations were made in a standardized automatic mixer with a kneading time in accordance with EN196-1, September 2016 and then introduced into 4 cm × 4 cm × 16 cm prismic moulds. The latter have gone to the shock table to be homogenized and close the voids in order to improve the compactness of the specimens. The specimens were stored in a humid room for 24 hours and then in tanks containing water at a temperature of 20˚C ± 2˚C until the scheduled date of the mechanical tests. A part of the test pieces was kept at room temperature for immersion absorption tests.

(a) (b) (c)

Figure 1. Glass sands (a) white, (b) brown, (c) green.

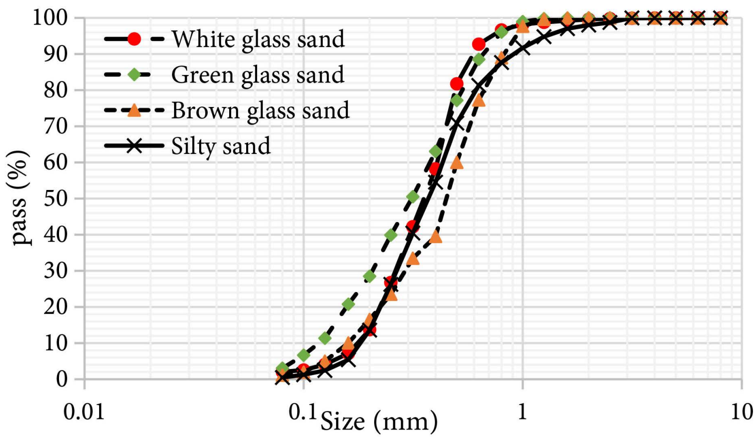

Figure 2. Particle size distributions of glass sands and silty sand.

Table 1. Physical characteristics of glass sand and silty sand [6].

Physical properties	White glass sand	Green glass sand	Brown glass sand	silty sand
Sand Equivalent Test (ES)	71.00	71.00	71.00	76
Absolute density (dab)	2.40	2.50	2.50	2.63
Apparent density (dap)	1.30	1.25	1.25	1.38
Fineness modulus (Mf)	1.59	1.4 0	1.80	1.79
HAZEN's coefficient (Cu)	2.22	3.17	2.94	2.44
Curvature coefficient (Cc)	0.98	0.97	0.99	0.89
Absorption Coefficient after 72 hours	30.14	29.11	23.33	22.46

Table 2. Mass composition of the mixtures studied.

Cement mass C	Sand mass		Glass sand mass		Water mass E	W/C ratio
(g)	(g)	(%)	(g)	(%)	(g)	
					225	0.50
450	1350	100	0	0	202.50	0.45
					180	0.40

Continued

450	1215	90	135	10	225	0.50
					202.50	0.45
					180	0.40
	1080	80	270	20	225	0.50
					202.50	0.45
					180	0.40
	945	70	405	30	225	0.50
					202.50	0.45
					180	0.40
	810	60	540	40	225	0.50
					202.50	0.45
					180	0.40
	675	50	675	50	225	0.50
					202.50	0.45
					180	0.40
	337.50	25	1012.5 0	75	225	0.50
					202.50	0.45
					180	0.40
	0	0	1350	100	225	0.50
					202.50	0.45
					180	0.40

For each specimen, we determined the apparent densities, the three-point bending and compression strengths at the 7th and 28th day of age. Each result is the average of a series of three values from the same assay.

3. Test Results and Discussion

3.1. Physical Properties

Table 3 shows the results of the apparent densities of glass and glass-free mortar samples. There is a slight increase in the densities of the different mixtures from the 7th to the 28th day. This is due to the low porosity of the test pieces and the absorption of water during the cure.

The results of the apparent densities at the 7th and 28th days of age show that the addition of fine glass sand by substitution for silty sand leads to a decrease in mortar densities which is evolutionary with the increase in the rate of incorporation. This is due to the low absolute density of glass sands which varies from 2.40 to 2.50 against 2.68 for silty sand. It should also be noted that the densities of the test pieces decrease with the decrease of the ratio W/C. The best results are obtained for the ratio W/C = 0.50.

Table 3. Apparent densities.

Rate	E/C	White glass sand		Brown glass sand		Green glass sand	
		7 days	28 days	7 days	28 days	7 days	28 days
0%	0.5	2.27	2.31	2.27	2.31	2.27	2.31
	0.45	2.24	2.28	2.24	2.28	2.24	2.28
	0.4	2.19	2.20	2.19	2.20	2.19	2.20
10%	0.50	2.23	2.27	2.18	2.22	2.18	2.18
	0.45	2.22	2.20	2.12	2.11	2.21	2.33
	0.40	2.12	2.13	2.07	2.10	2.17	2.17
20%	0.50	2.14	2.18	2.19	2.19	2.30	2.31
	0.45	2.11	2.11	2.14	2.16	2.14	2.23
	0.40	2.08	2.09	2.12	2.09	2.20	2.19
30%	0.50	2.14	2.16	2.21	2.15	2.22	2.22
	0.45	2.05	2.11	2.13	2.12	2.18	2.22
	0.40	2.07	2.08	2.12	2.14	2.13	2.18
40%	0.50	2.08	2.11	2.13	2.16	2.17	2.12
	0.45	2.10	2.11	2.07	2.16	2.13	2.14
	0.40	2.03	2.13	2.08	2.12	2.12	2.14
50%	0.50	2.07	2.10	2.17	2.21	2.11	2.20
	0.45	2.06	2.06	2.09	2.14	2.07	2.14
	0.40	1.99	2.07	2.08	2.10	2.11	2.09
75%	0.50	1.99	2.00	2.11	2.12	2.09	2.09
	0.45	1.98	2.00	2.10	2.10	2.06	2.06
	0.40	1.95	2.00	2.04	2.09	2.03	2.06
100%	0.50	2.04	2.08	2.06	2.09	2.05	2.04
	0.45	1.99	2.09	2.04	2.08	1.99	2.01
	0.40	2.06	2.05	2.01	2.05	1.78	1.78

With regard to absorption by immersion of the specimens, Table 4 shows that the absorption decreases with an increase in the W/C ratio and decreases according to the increase in the rate of substitution. This is explained by the high absorption coefficient of the glass sands used which vary from 23.33% to 30.14% against 22.46% for the silty sand used and the additional porosity generated by the glass sands. Figure 3 shows the water absorption rate of optimum compressive strength.

Referring to earlier work, the absorption of glass mortars also depends on the size of the glass grains. This is reflected in the work of Ayite [5] which has succeeded in showing that mortar made with 0/5 glass sand substituted by 10%, 20%, 30% reduces water absorption compared to a control mortar without glass.

Table 4. Compressive strength and absorption rate.

Rate	E/C	White glass sand			Brown glass sand			Green glass sand		
		7 days	28 days	Absorption (%)	7 days	28 days	Absorption (%)	7 days	28 days	Absorption (%)
0%	0.50	15.26	21.13	4.61	15.26	21.13	4.61	15.26	21.13	4.61
	0.45	12.00	20. 44	4.43	12.00	20. 44	4.43	12.00	20.44	4.43
	0.40	10.76	13.33	5.79	10.76	13.33	5.79	10.76	13.33	5.79
10%	0.50	15.36	22.54	4.89	14.21	18.40	3.52	14.28	19.68	5.24
	0.45	11.50	16.02	5.32	9.88	12.98	4.06	13.17	16.62	4.88
	0.40	9.27	11.37	5.85	6.61	9.01	7.39	9.32	11.29	6.95
20%	0.50	13.90	17.76	5.76	15.21	21.00	3.83	15.04	21.56	5.01
	0.45	10.93	12.65	6.01	13.81	14.99	4.44	11.09	16.20	5.40
	0.40	8.51	8.86	8.13	7.43	9.11	8.49	7.69	11.51	6.81
30%	0.50	13.35	14.79	4.95	14.35	21.25	4.16	13.30	19.00	4.74
	0.45	9.65	13.87	6.30	12.86	14.40	4.44	10.05	19.22	5.66
	0.40	9.21	8.38	8.96	6.05	10.86	8.36	7.36	11.56	7.91
40%	0.50	12.51	16.26	4.70	16.26	19.31	4.34	14.99	20.71	5.17
	0.45	9.95	12.48	6.65	7.43	15.54	5.18	11.72	13.42	6.09
	0.40	7.86	8.80	8.66	6.02	10.72	7.59	8.59	10.55	6.68
50%	0.50	11.00	16.27	4.80	14.41	20.00	4.34	14.18	19.36	4.31
	0.45	9.42	12.09	5.72	12.36	14.52	5.79	10.54	17.70	5.80
	0.40	7.85	8.88	10.25	9.14	10.54	9.41	8.47	9.85	7.81
75%	0.50	9.94	15.42	6.91	15.60	22.64	4.51	14.03	15.86	4.52
	0.45	8.61	10.33	9.93	10.97	15.78	6.84	10.91	15.56	7.82
	0.40	7.48	8.35	11.90	8.38	9.56	7.79	8.17	9.47	11.12
100%	0.50	10.10	14.22	4.88	13.62	20.97	4.45	13.01	18.98	7.33
	0.45	8.36	14.24	8.91	9.91	16.95	6.50	8.69	12.08	11.74
	0.40	7.55	9.71	11.60	7.60	12.84	9.43	7.73	10.73	11.74

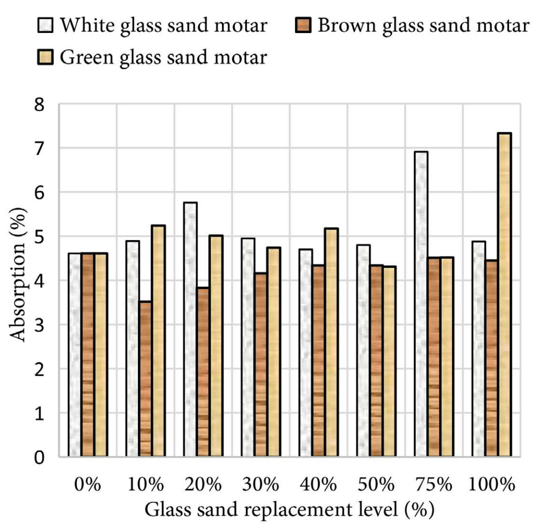

Figure 3. Water Absorption rate of optimum compressive.

This is logical because as the glass becomes coarse, the absorption coefficient of the glass sand decreases and therefore the absorption of mortars decreases.

3.2. Mechanical Properties

The results of the mechanical compression tests presented in **Table 4** show a normal evolution of the resistances from the 7th to the 28th days for all the W/C assays and glass sands substitutions performed. Nevertheless, there is a decrease in the strength of glass and glass-free mortar specimens with the reduction of the water dosage from 0.50 to 0.40. The same applies to the substitution rate of white glass sands which negatively influences the resistance of mortars above 10% substitution at 28 days of age.

For brown and green glass sands, the compressive strengths degrade only with the decrease of the W/C dosage and above 10% substitution, are superior to the resistances of the white glass sand mixtures. This is due to the more spreading particle size of the brown (Cu = 2.94) and green (Cu = 3.17) glass sands compared to the white green (Cu = 2.22) sand despite their fine-ness [6].

These results confirm the work of Ayite [5] which has been able to show that the resistances in compression are high when the glass sand used is coarse and has a spread particle size.

Moreover, these results also confirm the work of Kiang HWEE [9] which has been able to show that the mechanical properties of glass sand mortars are compromised by the micro-cracking of glass sand and the mechanical resistance of white glass mortars are lower than others due to the reactivity of white (clear) glass which is potentially harmful and leads quickly to the alkali-silica reaction [9]. He obtained these glass reactivity results following accelerated mortar bar tests according to ASTM C 1260standard [9].

The best results are obtained for the ratio W/C = 0.50 (**Figure 4**) with values which tend to exceed the control mortar of silty sand. Thus, glass mortar mixes absorb additional water to wet the aggregates while indirectly reducing the bound water used to completely hydrate the cement and form binding hydrate crystals.

Compared to other recycling aggregates such as recycled sand, the compressive strengths obtained are better due to the very high absorption of these sands from building waste [10].

In three-point bending, there is a logical increase in bending strength from the 7th to the 28th days. The best results (**Table 5**) are obtained for the W/C ratio = 0.50 for all the glass and glass-free test pieces. However, these bending strengths on the 7th and 28th day of glass specimens are approximately lower than those of glass specimens. Thus, the glass sand does not improve the bending strength of the mortar test pieces. Nevertheless, it should be noted that the resistances obtained are ±17% of the control mortar without glass. This is acceptable from a three-point bending point for a recycling aggregate.

In short, for the three glass colours used, the optimal dosage of the glass sand mortar to this 0/2 glass particle size com-pared to the silty sand (0/2) is:

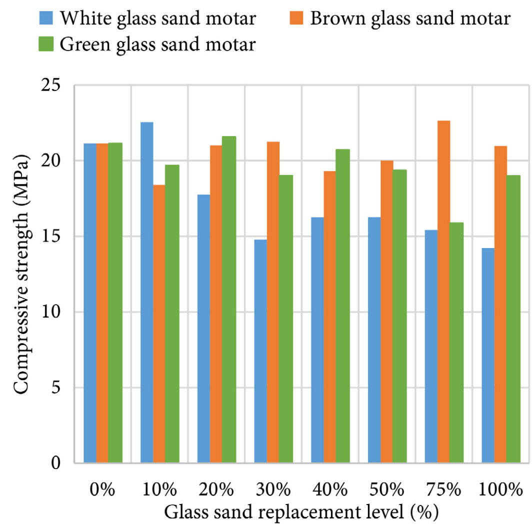

Figure 4. Optimum values of compressive strength.

Table 5. Bending strength.

Rate	E/C	White glass sand		Brown glass sand		Green glass sand	
		7 days	28 days	7 days	28 days	7 days	28 days
0%	0.5	3.69	4.61	3.69	4.61	3.69	4.61
	0.45	3.38	3.85	3.38	3.85	3.38	3.85
	0.4	2.55	2.84	2.55	2.84	2.55	2.84
10%	0.50	4.16	5.13	3.26	4.09	3.39	3.83
	0.45	3.59	3.86	2.69	2.38	2.99	4.04
	0.40	2.84	3.06	2.01	1.87	2.54	2.80
20%	0.50	3.57	4.42	3.42	3.88	4.00	4.16
	0.45	2.73	2.60	2.92	3.26	2.35	3.34
	0.40	2.20	2.26	1.97	2.17	2.26	3.30
30%	0.50	3.22	4.13	3.49	4.41	3.70	4.20
	0.45	2.31	3.04	2.76	2.92	2.94	4.23
	0.40	2.16	2.59	2.03	2.82	2.24	3.01
40%	0.50	3.06	4.08	3.39	4.28	3.12	3.97
	0.45	2.21	2.85	2.37	3.20	2.74	3.21
	0.40	1.85	2.44	1.94	2.56	2.39	2.78
50%	0.50	3.04	4.02	3.65	4.84	3.35	4.71
	0.45	2.40	3.08	2.62	3.66	2.44	3.98
	0.40	1.87	2.09	2.32	2.78	2.22	2.80
75%	0.50	2.46	3.83	3.59	4.80	3.09	4.39
	0.45	2.01	3.17	2.70	3.42	2.66	3.66
	0.40	2.03	2.68	2.24	2.88	2.01	2.61
100%	0.50	2.83	5.11	3.26	4.78	2.78	4.22
	0.45	2.16	3.96	2.96	4.60	2.02	3.32
	0.40	2.19	3.41	2.35	3.68	1.80	2.95

- 10% for white glass sand: 135 g glass, 1215 g silty sand and 225 g water, W/C = 0.50;
- 20% for green glass sand: 270 g glass, 1080 g silty sand and 225 g water, W/C = 0.50;
- 75% for brown glass sand: 1012.5 g glass, 337.5 g silty sand and 225 g water W/C = 0.50.

4. Conclusions

This experimental study aims at the possibility of using fine glass sands from the crushing and grinding of glass waste as a substitute for silty sand in the mortar in order to enhance it and reduce environmental pollution. For this purpose, mortar formulations studies were carried out on three colours of crushed glass and composed at sizes approaching the particle size curve of the silty sand. It follows that:

- Fine glass sand (0/2) has more absorption than silty sand (0/2).
- The W/C = 0.50 ratio provides the best compressive strengths of glass mortars.
- The use of 0/2 class fine glass sand in construction is possible, but the colour, the water dosage and particle size of the glass influence the compressive strengths.
- The formulation of glass mortars for optimum compressive strength requires a 10% substitution for white glass sand, 20% for green glass sand and 75% for brown glass sand.
- Fine brown glass sand (0/2) is the best type of fine glass sand to use for non-adjuvanted mortar.
- The color of fine glass aggregates (0/2) influences the physical and mechanical properties of mortar.

Furthermore, the studies have been conducted on a CEMII composite cement mortar. However, it would be beneficial to extend these research efforts to other types of cements (such as CEMI), incorporate a plasticizer into the mortar, and study the reactivity of glasses using the ASTM C 1260 method.

Acknowledgements

Our thanks go to the Laboratory of Structures and Mechanics of Materials of the Polytechnic School of the University of Lomé, the Regional Training Center for Road Maintenance (CERFER) and the FORMATEC Research and Development Structure (ERDF) for their contribution to carrying out of this work.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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