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Research Paper

Properties of Binary Blended Cement Mortars Containing Glass Powder and Steel Slag Powder

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The large quantity of waste or by-product materials (such as waste glass and steel slag) released to landfills is considered to be a real problem. The use of these materials as cement replacements makes it possible to solve this problem and reduce the quantity of carbon dioxide emitted from the cement manufacturing process. This paper presents the effect of waste glass powder (GP) and steel slag powder (SSP) on the properties of blended cement mortar. The flow, compressive strength, direct tensile strength and dry density of cement mortar containing GP and SSP as cement replacements with and without superplasticizer (SP) are studied and compared with the control mix. The results show that the glass and steel slag powders, once they are simultaneously added as a ternary blended cement mortar, reduce the water binder ratio required to achieve flowability. Additionally, the compressive strength results of such blended mortar showed that the increased GP content exhibits better performance than that of slag powder for the same level of waste materials replacements.

Key words: glass powder; steel slag powder; flowability.

1. Introduction

Cement manufacturing emits about 5–7% of global anthropogenic greenhouse gas emissions. The high contribution comes from the production of cement whose each ton releases about 0.8 to 1 tons of the carbon dioxide (CO_2) that is being emitted to the atmosphere from both fuel combustion and calcination process of raw materials [1]. Local materials such as glass and steel slag powders are available as partial replacements of cement and offer a viable strategy to reduce the cement proportion use [1–3]. Actually, these products reduce the amount of carbon dioxide released into the atmosphere, whereas Portland cement manufacturing increases those emissions. Using these materials not only helps to reduce the amount of CO_2 emissions and cost of cement but it also provides a partial solution to environmental and ecological issues all over the world caused by huge landfills, resulting in serious environmental pollutions in terms of quantity and associated health risks faced by all parts of the world [4, 5]. Worldwide, around 130 million tons of glass are currently produced annually and about 79% left in landfills [html]. According to Bignozzi *et al.* [6], the chemical composition of the glass plays a major role in creating the conditions for developing pozzolanic and/or alkali-silica reactions. While according to Patel *et al.* [7] and Vijayakumar *et al.* [8], GP with particles smaller than 75 μm does not induce an alkali-silica reaction (ASR). Nassar and Soroushian [9] observed that the grinding of pozzolanic materials to micro-scale for particle size activates the reactions with cement hydrates forming secondary calcium silicate hydrate (C–S–H). However, Patel *et al.* [7] observed through SEM and EDX analysis that the waste GP behaves as filler in early ages of curing and the propagation of the C-S-H compound may happen at later ages signifying its pozzolanic nature. Another study was conducted by Tamanna *et al.* [10] who found that the calcium hydroxide $Ca(OH)_2$ has been decreased while the C-S-H formation was increased simultaneously at 90 days for particle sizes of 75–38 μm and lower than 38 μm.

Matos and Sousa-Coutinho [11] also found that the notable strength activity indices were obtained at 90 days of curing for mortar containing GP with a significant increase between 28 and 90 days, which means that the pozzolanic activity occurred. Ibrahim and Meawad [12] found that the ions do not have effects on the performance of the formation of C-S-H, which is the main phase of the pozzolanic reaction. According to studies conducted by Matos and Coutinho [11], Islam *et al.* [13] and Aliabdo *et al.* [14], the GP can be considered as pozzolanic-cementitious material according to requirements of ASTM C 618 [15]. Aliabdo *et al.* [14] studied the GP contents that were 0%, 5%, 10%, 15%, 20%, and 25% by weight of cement. The test results showed that the use of 10% of the GP as cement replacement improved the compressive strength of mortar by about 9.0%. Generally, the use of GP as a partial cement replacement up to 15.0% improved the concrete properties for the mixes modified with GP.

Steel slags (SS) are industrial by-products of steel manufacturing. The common mineral compositions for SS are C_2S, C_3S, C_2F, C_4AF, Fe_3O_4, and RO phase (CaO–FeO–MnO–MgO solid solution), free CaO and free MgO. According to the World Steel Association Global, the Middle East produced 45.3 Mt of crude steel in 2019, and the production of one ton of steel tends to produce about 130–200 kg of SS, depending on the steel production process and the composition of steel [16, 17]. According to Shi [16], the chemical composition and cooling of molten SS have a great effect on the physical and chemical properties of solidified SS.

Wang *et al.* [18] observed that the hydration rate of SS increases as its specific surface area increases. Liu *et al.* [19] observed that the allowed amount of particle size with more than 65 μm is less than 10% compared to particle size less than 65 μm. Kourounis *et al.* [20] and Wang *et al.* [21] observed that the SS retards the hydration of the blended cement due to the contained C_2S morphology. This is because βC_2S turns to γC_2S when the temperature drops below 500 °C during cooling crystallization. The cooling process of SS is long enough to allow the lattice rearrangement, so a considerable amount of C_2S takes the form of γC_2S. The activity of γC_2S is much lower than that of βC_2S, in addition to insufficiency in C_3S. So, the early age hydration is retarded, leading to a reduction in the early age compressive strength [22].

2. Objectives of the study

The objectives of this study are to produce eco-friendly mortar by the addition of GP and SSP as a replacement of cement in two stages: the first stage evaluates the pozzolanic effects of glass and steel slag powders, and the second stage consists of studying the properties of glass and steel slag powder-blended cement mortar.

3. Materials, experimental parameters and testing

3.1. Material properties

Ordinary Portland cement Type I is obtained from the Badoush Expansion Cement Factory. This cement type satisfies the IQS: 5/1984 [23] specification guidelines. Chemical analysis of cement is shown in Table 1, while physical characteristics are shown in Table 2. The specific gravity values for each of glass and steel slag powders with particles finer than 63 μm are 2.62 and 3.47, respectively. Chemical analyses of glass and steel slag powders are presented in Tables 3 and 4,

Table 1. The chemical composition of ordinary Portland cement.

Constituent	Content percent [%]	Limits of IQS 5/1984
CaO	62.5	–
SiO_2	20.91	–
Al_2O3	5.96	–
MgO	3.8	$\geq 5.0\%$
Fe_2O_3	2.53	–
SO_3	2.32	$\geq 2.8\%$
L.O.I	1.45	$\geq 4.0\%$
C_3S	39.5	–
C_2S	30.16	–
C_3A	11.5	–
C_4AF	7.7	–

Table 2. Physical characteristics of ordinary Portland cement.

Test	Produced cement	Limits of IQS 5/1984
Initial setting time [min]	143	min 45
Final setting time [min]	175.5	max 600
Blain fineness [cm^2/g]	3398	more than 2300
Compressive strength [N/mm^2] 3 days 7 days	 31.64 39.3	 ≥ 16 ≥ 24

Table 3. Chemical composition of GP.

Constituent	Content percent [%]	Pozzolan class N ASTM C618
CaO	10.43	–
SiO_2	73.7	–
Al_2O3	0.72	–
MgO	1.27	–
Fe_2O_3	0.38	–
SO3	–	4
Na_2O	12.71	–
K_2O	0.70	–
TiO_2	0.086	–
L.O.I	–	10
$SiO_2 + Al_2O_3 + Fe_2O_3$, min. percent	74.8	Min. 70

Table 4. Chemical composition of SSP.

Constituent	Content percent (%)	ASTM C989
CaO	44.27	–
SiO2	18.73	–
Al2O3	2.18	–
MgO	5.54	–
Fe_2O3	22.69	–
SO3	0.45	max 2.5
Na_2O	–	–
K_2O	0.01	–
L.O.I	6.12	10
Total alkalies (Na_2O + 0.658 K_2O)	0.00658	min 0.60% max 0.90%

respectively. SP has been provided by Sika ViscoCrete hi-tech 1316. This SP is conformed to ASTM C494 – Type F and G [24]. The natural river sand is the fine aggregate used in this study and was obtained from the Kanhash region in Mosul, Iraq. The specific gravity, absorption and fineness modulus of sand are 2.66, 1% and 3, respectively. The sand grading analysis is conformed to IQS 45/1984 [25] and given in Table 5. Potable water was used for mixing and curing processes.

Table 5. Grading of fine aggregate.

Sieve No. [mm]	Cumulative passing [%]	Limits of IQS 45/1984
3/8″	100	100
No. 4 (4.75)	92	90–100
No. 8 (2.36)	80	75–100
No. 16 (1.18)	58	55–90
No. 30 (0.60)	39	35–59
No. 60 (0.30)	23	8–30
No. 100 (0.15)	7	0–10

3.2. Experimental parameters

The experimental part of this research is conducted in two stages. The first stage includes the evaluation of the pozzolanic effect of GP and SSP using the strength activity index according to ASTM C618 [15] and ASTM C989 [26], respectively. Whereas the second stage presents the use of GP and SSP as partial replacements of cement, and the cement mortar of the test mix incorporates different percentages of glass and steel slag powders. Mix proportions are described in Tables 6 and 7. The cement sand ratio is 1 : 2.75, and the water binder ratio

Table 6. Test results of mortar mixes without SP.

Mix No.	Cement [%]	Replacement ratio [%]		W/CM [%]	Flow [%]	Compressive strength [MPa]		Direct tensile strength [MPa], 28 days	Bulk dry density [gm/cm^3], 28 days
		GP	SSP			7 days	28 days		
M0	100	–	–	0.58	111	21.038	31.26	3.089	1.974
M1	80	10	10	0.56	112	17	30.26	2.723	1.958
M2	75	15	10	0.56	111	15.296	21.461	2.153	1.906
M3	75	12.5	12.5	0.56	109	14.932	23.419	2.167	1.944
M4	70	15	15	0.56	113	13.52	23.16	1.925	1.945
M5	70	12	18	0.56	115	11.31	22.197	1.898	1.909
M6	70	18	12	0.56	115	13.52	19.84	1.861	1.881

Table 7. Test results of mortar mixes with SP.

Mix No.	Cement [%]	Replacement ratio [%]		W/CM [%]	SP [%]	Flow [%]	Compressive strength [MPa]		Direct tensile strength [MPa], 28 days	Bulk dry density [gm/cm^3], 28 days
		GP	SSP				7 days	28 days		
A0	100	–	–	0.50	0.8	115	28.705	35.007	3.654	1.891
A1	80	10	10	0.48	0.8	109	23.254	32.187	3.283	1.841
A2	75	15	10	0.48	0.8	112	21.687	31.958	3.112	1.854
A3	75	12.5	12.5	0.48	0.8	110	20.869	31.019	3.147	1.869
A4	70	15	15	0.48	0.8	113	15.024	27.625	2.797	1.872
A5	70	12	18	0.48	0.8	112	14.687	21.859	2.857	1.856
A6	70	18	12	0.48	0.8	115	16.067	24.668	2.939	1.854

varies from 0.58 to 0.56 by weight of binder content to maintain flowability of mortars, which conforms to ASTM C1437 [27] for all the mixes, and 0.5 to 0.48 by weight of binder content to maintain flowability of mortars for all the mixes by the virtue of SP. The dosage of SP remains constant for all mortar mixes (0.8% by weight of binder).

3.3. Test methods

As mentioned before, this research work is divided into two stages. Each stage includes some related standard tests. The strength activity index was investigated in the first stage. For the second stage, three cube specimens of size of $50 \times 50 \times 50$ mm were used for each mix in order to test the compressive strength at various ages of 7 and 28 days according to ASTM C109 [28]. The flow test for mixes was performed according to ASTM C1437 [27] with a designed flow of $110 \pm 5\%$ for fresh mortar. The three bracket specimens were cast for the direct tensile strength and tested at 28 days according to ASTM C190 [29]. Finally, three cubes of $70 \times 70 \times 70$ mm samples were used for each mix to test the density according to ASTM C642 [30]. The cube and bracket specimens were left in the molds for 24 hours after casting. After demolding, the specimens were kept in water until the time of the test.

4. Test results and discussions

4.1. Pozzolanic effect of GP and SSP (first stage)

According to ASTM C618 specification limits, ($SiO_2 + Al_2O_3 + Fe_2O_3$) minimum requirement for a standard pozzolana is 70%. The standard sets maximum limit of SO_3, loss of ignition and moisture content are 4%, 10%, and 3%, respectively. As shown in Table 2, the GP samples can be considered to have pozzolanic behavior in the cementitious system. Modified cement mortar with 20% GP as a partial cement replacement should give at least 75% of the control mortar strength at the curing ages of 7 and 28 days to be considered a cementitious material. Thus, the strength activity index at 7 and 28 days was 78.3% and 91.88%, respectively.

SSP can also be considered as a pozzolanic material according to ASTM C989 specification limits. A modified cement mortar with 50% SSP as a partial cement replacement should give at least 75% of the control mortar strength at the ages of 7 or 28 days to be considered a cementitious material. The strength activity indices for the ages of 7 and 28 days were 62.04% and 80.36%, respectively. Similar results were also obtained by Zhu *et al.* [31] as they also found that the reduced ratio of $CaO/(SiO_2 + P_2O_5)$ in SS may drop the level of compressive strength of cement mortar accordingly.

4.2. Effect of using GP and SSP as cement replacement of mortar (second stage)

4.2.1. Flowability. The flowability (workability) has been measured according to ASTM C1437. Due to using standard sand in this research, the effects of adding supplementary cementitious materials are more obvious. The water to binder ratio is 0.58 and 0.6 is required to obtain the flowability between 105% to 115% using 20% from each of GP and SSP, respectively, as partial replacement of cement. The comparison between this blended mortar (20% from each of SSP or GP) with control mix (w/b = 0.58) indicates that SSP needs more water than GP (the same water-cement ratio of control) to achieve the flowability between 105% to 115% according to specification. This is because SSP has irregular particle shape and coarse surface textures according to Qiang *et al.* [32] and Li *et al.* [33]. The irregular shape of the particles generates high frictional forces between them and consequently leads to decreased flowability of the mixes [34], but the results of flow of mortar containing GP were 106% compared with the control mix with the flow of 111% at the same water requirement. Although GP exhibits angular particle shape through the SEM analysis observed by Pereira de Oliveira *et al.* [35] and Shi *et al.* [36], the specific surface area of GP needs more water compared with the specific surface area of cement.

The water binder ratio to obtain the flowability of the mortar mixes containing glass and steel slag powders (e.g., 10% GP and 10% SSP) decreased in comparison with the control mix (without replacement). This phenomenon can be attributed to the fact that the mixture containing GP and SSP improves the filling effect, thus leading to significant improvement in packing density by lowering the required amount of water to fill the voids between particles [37].

With the increased packing density in the mixture, cement particles and other particles are close to each other, and thus may lead to reduce the space needed to be filled by hydration products [38]. Therefore, the ternary blended cement in mixes containing GP and SSP, which exhibited the ideal particle-size distribution, improved the gradation of binder materials to achieve a densely graded binder system [37, 39]. From the results observed, the glass and steel slag powders may enhance the packing density in ternary mortar mixtures with a higher effect than that of the control mix, or mortar contains either GP or SSP separately.

The results of the flow illustrated in Table 6 show that the increased glass and steel slag powders substitution level increases the flow of mortar, especially at 30% replacement of cement, and the effect of packing density seems more obvious.

The results of flow of ternary blended cement in mixes containing GP and SSP with SP are illustrated in Table 7. It can be seen that the water to binder ratio for obtaining the flowability between 105% to 115% is less than that required for the control mix (similar effect was obtained with mortar mixes without super plasticizer).

With the addition of SPs, the packing density of the solids increased. At high packing density (low w/b), the number of particles that contact each other increases substantially [40]. The flow increased at the same water binder ratio, with the GP content increase compared with the SSP content. This can be attributed to the presence of glass powder, in which, according to Lu *et al.* [41], GP has a smooth surface texture compared to SSP.

4.2.2. Compressive strength. Three cubes were tested according to ASTM C109, at each age for the compressive strength determination of cubes with various percentages of GP and SSP as a partial replacement of cement. Mortar mixes were examined at the ages of 7 and 28 days. From the results tabulated in Table 7, it can be observed that the replacement of 20% of GP and 20% of SSP compared with the control mix, caused the compressive strength to decrease by 21.7% and 37.6% at 7 days, respectively. While the results of compressive strength decreased by about 8% and 19.6% at 28 days for the same replacement ratio of GP and SSP, respectively. These results are in agreement with the other experimental results by Patel *et al.* [7] studied through the SEM and EDX analysis the microstructure for GP- blended cement and control pastes, which are identical in morphology with greater surface area, confirming that its filler effect and the growth of C-S-H gel is initiated as the Ca/Si ratio decrease. Hea *et al.* [42] found that the use of less than 20% of GP content reduced the early ages' compressive strengths but increased the later ages' compressive strengths. However, with the GP contents increase, the ranges of concrete strengths are higher than that of concrete strengths for concrete containing SSP contents. This is due to the slow development of hydration products for SSP as the hydration products of SSP slowly increase with time [18].

The compressive strength of the various mixes of mortars (containing glass and steel slag powders) decreased remarkably compared with the control mix (without replacement). However, it has been increased noticeably compared with the GP or SSP replaced separately at a similar replacement ratio. For example, with a partial replacement of cement by 10% GP and 10% SSP, the compressive strength of mortar decreased by about 19.2% and 3% at 7 and 28 days, respectively, without SP. Such improvement can be related to the synergistic effect between these two supplementary cementitious materials (GP and SSP) when they are simultaneously added, which increases the filling effect with a greater level than that of the effect of GP or SSP added separately with the same replacement ratio improving the packing density of cementitious materials [43, 44]. Although the reactivity of these materials was low (especially the SSP), the good strength level obtained can be attributed to the increased number of the hard anhydrous inclusions, which are closer to each other and embedded in hydrate regions of smaller dimensions [45]. From the results illustrated in Fig. 1 and Tables 6 and 7, it can be observed that the compressive strength decreased by about 19.2%, 27%, 29%, 36%, 46%, and 35% for mixes M1, M2, M3, M4, M5 and M6, respectively at 7 days compared with the control mix. Meanwhile, the compressive strength incorporating SP in the mortar mixes decreased by about 18%, 24%, 27%, 47.7%, 48%, and 44% for mixes A1, A2, A3, A4, A5, and A6,

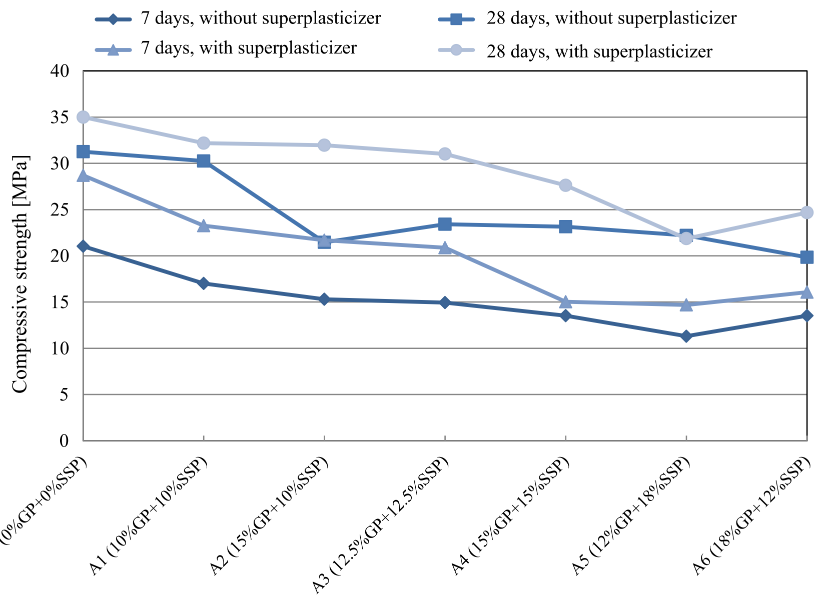

Fig. 1. Effects of glass and steel slag powders on the compressive strength of mortar.

respectively, compared with the control mix. While the compressive strength decreased by about 3%, 31.5%, 25.1%, 26%, 29%, and 37% for mixes M1, M2, M3, M4, M5, and M6, respectively, at 28 days compared with the control mix. Meanwhile, the compressive strength of mortar mixes with the SP decreased by about 8%, 8.7%, 11.4%, 21.6%, 37.5%, and 29.5% for mixes A1, A2, A3, A4, A5, and A6, respectively, compared with the reference mix. The reduction in the compressive strength is attributed to the lower reactivity of supplementary cementitious materials compared with ordinary Portland cement as has been mentioned above.

4.2.3. Direct tensile strength. Figure 2 and Tables 6 and 7 show the test results for the direct tensile strengths at 28 days. The direct tensile strengths slightly decreased with the increased replacement ratio of glass and steel slag powder compared with the control mix. However, it can be noticed that the direct tensile strength increased more evidently with the increased SSP content other than the GP content at all mixes with or without SP. For example, direct tensile strength increased at mix M3 and M5 compared with M2 and M6 without SP. While at 30% replacement ratio level, the mix containing 18% GP exhibited higher performance than that of mix containing 18% SSP.

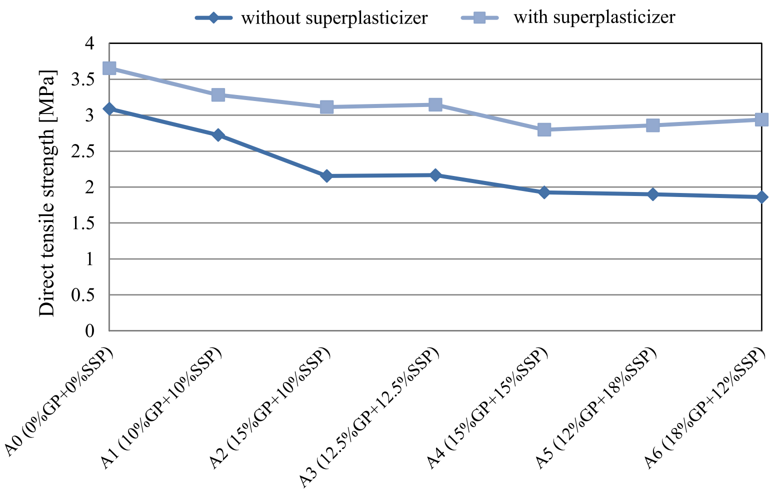

Fig. 2. Effects of glass and steel slag powders on the direct tensile strength of mortar at 28 days.

4.2.4. Dry density. The mortar's oven-dry density containing glass and steel slag powders was specified based on ASTM C 642. The results for the dry density test at 28 days are tabulated in Tables 6 and 7. It is observed that the dry density slightly decreased with the addition of glass and steel slag powders as

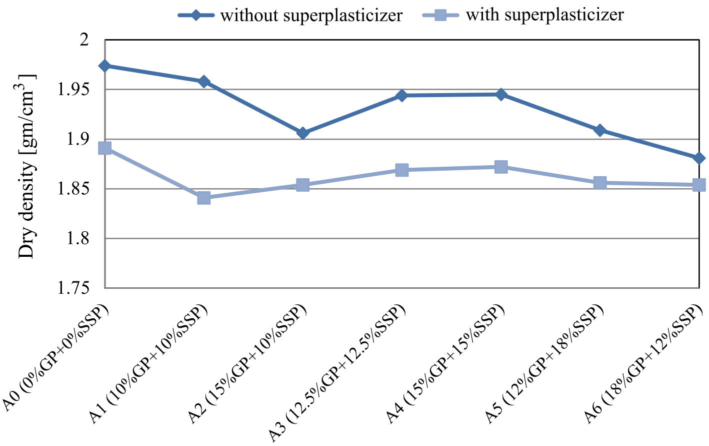

Fig. 3. Effects of glass and steel slag powders on the dry density of mortar at 28 days.

a replacement ratio compared with the control mix. However, the results indicate (Fig. 3) that the increase of SSP increased the overall density of the mortar. While the increase of the GP content compared with SSP in mortar mixes decreased the density.

5. Conclusions

The following conclusions from the results of this study are as follows:

1) Ternary blends of glass and steel slag powders produced suitable flow, the quantity of water required to achieve the flowability was smaller than the quantity of water needed to achieve the flowability of the control mix. However, with the increased GP content, the mix flow increased unlike the one with the increased SSP content at the same water binder ratio.
2) The compressive strength of mortar decreased with the increased replacement ratio of cement by GP and SSP. However, the replacement of 30% of cement by glass and steel slag powders still gave the strength of structural mortar.
3) The GP content decreased the dry density of cement mortar while the SSP had less effect on the dry density of mortar.
4) The CO_2 emission reduction can be recorded by approximately 19.9% and 29.8% for 20% and 30%, respectively, due to glass and steel slag powders additions.

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References

1. Sabnis G.M., *Green Building with Concrete, Sustainable Design and Construction*, 2nd ed., CRC Press, Boca Raton, Florida, 2016.
2. Li Z., *Advanced Concrete Technology*, John Wiley & Sons, Hoboken, New Jersey, 2011.
3. Belie N.D., Soutsos M., Gruyaert E. [Eds], *Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials*, Springer International Publishing, 2018, doi: 10.1007/978-3-319-70606-1.
4. Siddique R., *Waste Materials and By-Products in Concrete*, Springer-Verlag, Berlin, Heidelberg, 2008, doi: 10.1007/978-3-540-74294-4.
5. Jani Y., Hogland W., Waste glass in the production of cement and concrete – A review, *Journal of Environmental Chemical Engineering*, **2**(3): 1767–1775, 2014, doi: 10.1016/j.jece.2014.03.016.
6. Bignozzi M.C., Saccani A., Barbieri L, Lancellotti I., Glass waste as supplementary cementing materials: The effects of glass chemical composition, *Cement & Concrete Composites*, **55**: 45–52, 2015, doi: 10.1016/j.cemconcomp.2014.07.020.
7. Patel D., Tiwari R.P., Shrivastava R., Yadav R.K., Effective utilization of waste glass powder as the substitution of cement in making paste and mortar, *Construction and Building Materials*, **199**: 406–415, 2019, doi: 10.1016/j.conbuildmat.2018.12.017.
8. Vijayakumar G., Vishaliny H., Govindarajulu D., Studies on glass powder as partial replacement of cement in concrete production, *International Journal of Emerging Technology and Advanced Engineering*, **3**(2): 153–157, 2013.
9. Nassar R.-U.D., Soroushian P., Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement, Construction and Building Materials, **29**: 368–377, 2012, doi: 10.1016/j.conbuildmat.2011.10.061.
10. Tamanna N., Sutan N.M., Tuladhar R., Lee D.T.C., Yakub I., Pozzolanic properties of glass powder in cement paste, *Journal of Civil Engineering, Science and Technology*, **7**(2): 75–81, 2016, doi: 10.33736/jcest.307.2016.
11. Matos A.M., Sousa-Coutinho J., Durability of mortar using waste glass powder as cement replacement, *Construction and Building Materials*, **36**: 205–215, 2012, doi: 10.1016/j.conbuildmat.2012.04.027.
12. Ibrahim S., Meawad A., Assessment of waste packaging glass bottles as supplementary cementitious materials, *Construction and Building Materials*, **182**: 451–458, 2018, doi: 10.1016/j.conbuildmat.2018.06.119.
13. Islam G.M.S., Rahman M.H., Kazi N., Waste glass powder as partial replacement of cement for sustainable concrete practice, *International Journal of Sustainable Built Environment*, **6**(1): 37–44, 2017, doi: 10.1016/j.ijsbe.2016.10.005.
14. Aliabdo A.A., Abd Elmoaty A.M., Aboshama A.Y., Utilization of waste glass powder in the production of cement and concrete, *Construction and Building Materials*, **124**: 866–877, 2016, doi: 10.1016/j.conbuildmat.2016.08.016.
15. ASTM C 618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, *Annual Book of ASTM Standards*, 2003.
16. Shi C., Steel slag – its production, processing, characteristics, and cementitious properties, *Journal of Materials in Civil Engineering*, **16**(3): 230–236, 2004, doi: 10.1061/(ASCE)0899-1561(2004)16:3(230).

17. Furlami E., Tonello G., Maschio S., Recycling of steel slag and glass cullet from energy saving lamps by fast firing production of ceramics, *Waste Management*, **30**(8–9): 1714–1719, 2010, doi: 10.1016/j.wasman.2010.03.030.

18. Wang S., Wang C., Wang Q., Liu Z., Qian W., Jin C.Z., Chen L., Li L., Study on cementitious properties and hydration characteristics of steel slag, *Polish Journal of Environmental Studies*, **27**(1): 357–364, 2018, doi: 10.15244/pjoes/74133.

19. Liu F., Chen M.Z., Li F.Z., Li Q.L., Wu S.P., Sang Y., Effect of ground steel slag powder on cement properties, *Materials Research Innovations*, **19**(Sup 1): S1-150–S1-153, 2015, doi: 10.1179/1432891715Z.0000000001393.

20. Kourounis S., Tsivilis S., Tsakiridis P.E., Papadimitriou G.D., Tsibouki Z., Properties and hydration of blended cements with steelmaking slag, *Cement and Concrete Research*, **37**(6): 815–822, 2007, doi: 10.1016/j.cemconres.2007.03.008.

21. Wang Q., Yan P., Feng J., A discussion on improving hydration activity of steel slag by altering its mineral compositions, *Journal of Hazardous Materials*, **186**(2–3): 1070–1075, 2011, doi: 10.1016/j.jhazmat.2010.11.109.

22. Zhang X., Zhao S., Liu Z., Wang F., Utilization of steel slag in ultra-high performance concrete with enhanced eco-friendliness, *Construction and Building Materials*, **214**: 28–36, 2019, doi: 10.1016/j.conbuildmat.2019.04.106.

23. Iraqi Standard Specification, *Characteristics of OPC*, Central Agency for Standardization and Quality Control, No. 5, 1984.

24. ASTM C494, Standard Specification for Chemical Admixtures for Concrete, *Annual Book of ASTM Standards*, 2004.

25. Iraqi Standard, *The Ruins of the natural Resources used in the Concrete and Construction*, Central Agency for Standardization and Quality Control, No. 45, 1984.

26. ASTM C989, Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, *Annual Book of ASTM Standards*, 2019.

27. ASTM C1437, Standard Test Method for Flow of Hydraulic Cement Mortar, *Annual Book of ASTM Standards*, 2019.

28. ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens), *Annual Book of ASTM Standards*, 2020.

29. ASTM C190, Standard Test Method for Tensile Strength of Hydraulic Cement Mortars, *Annual Book of ASTM Standards*, 1985.

30. ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, *Annual Book of ASTM Standards*, 2013.

31. Zhu G., Hao Y., Xia C., Zhang Y., Hu T., Sun S., Study on cementitious properties of steel slag, *Journal of Mining and Metallurgy, Section B: Metallurgy*, **49**(2): 217–224, 2013, doi: 10.2298/JMMB120810006Z.

32. Qiang W., Mengxiao S., Jun Y., Influence of classified steel slag with particle sizes smaller than 20 μm on the properties of cement and concrete, *Construction and Building Materials*, **123**: 601–610, 2016, doi: 10.1016/j.conbuildmat.2016.07.042.

33. Li C., Xiao Y., Wu S., Chen Z., Wu S., Crack resistance of asphalt mixture with steel slag powder, *Emerging Materials Research*, **6**(1): 214–218, 2017, doi: 10.1680/jemmr.16.00009.

34. Khaleel O.R., Abdul Razak H., The effect of powder type on the setting time and self compactability of mortar, *Construction and Building Materials*, **36**: 20–26, 2012, doi: 10.1016/j.conbuildmat.2012.04.079.

35. Pereira de Oliveira L.A, Castro Gomes J.P., Santos P., Optimization of pozzolanic reaction of ground waste glass incorporated in cement mortars, [in:] PORTUGAL SB07-Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, pp. 928–934, 2007.

36. Shi C., Wu Y., Riefler C., Wang H., Characteristics and pozzolanic reactivity of glass powders, Cement and Concrete Research, **35**(5): 987–993, 2005, doi: 10.1016/j.cemconres.2004.05.015.

37. Kwan A.K.H., Fung W.W.S., Wong H.H.C., Water film thickness, flowability and rheology of cement–sand mortar, *Advances in Cement Research*, **22**(1): 3–14, 2010, doi: 10.1680/adcr.2008.22.1.3.

38. Mehdipour I., Khayat Kamal H., Effect of particle-size distribution and specific surface area of different binder systems on packing density and flow characteristics of cement paste, *Cement and Concrete Composites*, **78**: 120–131, 2017, doi: 10.1016/j.cemconcomp.2017.01.005.

39. Fennis S.A.A.M., Walraven J.C., Using particle packing technology for sustainable concrete mixture design, HERON, **57**(2): 73–101, 2012, http://heronjournal.nl/57-2/1.pdf.

40. Flatt R., Schober I., Superplasticizers and the Rheology of Concrete,[in:] *Understanding the Rheology of Concrete***,** Roussel N. [Ed.], Woodhead Publishing in Civil and Structural Engineering, pp. 144–208, 2012, doi: 10.1533/9780857095282.2.144.

41. Lu J.-X., Duan Z.-H., Poon C.S., Fresh properties of cement pastes or mortars incorporating waste glass powder and cullet, *Construction and Building Materials*, **131**: 793–799, 2017, doi: 10.1016/j.conbuildmat.2016.11.011.

42. Hea Z.-H., Zhan P.-M., Du S.-G., Liu B.-J., Yuan W.-B., Creep behavior of concrete containing glass powder, *Composites Part B: Engineering*, **166**: 13–20, 2019, doi: 10.1016/j.compositesb.2018.11.133.

43. Lothenbach B., Scrivener K., Hooton R.D., Supplementary cementitious materials, *Cement and Concrete Research*, **41**(12): 1244–1256, 2011, doi: 10.1016/j.cemconres.2010.12.001.

44. Peng Y., Hu S., Ding Q., Dense packing properties of mineral admixtures in cementitious material, *Particuology*, **7**(5): 399–402, 2009, doi: 10.1016/j.partic.2009.06.003.

45. Aïtcin P.-C., 17 – The Influence of the water/cement ratio on the sustainability of concrete, [in:] *Lea's Chemistry of Cement and Concrete* (5th ed.), Hewlett P.C., Liska M. [Eds], Butterworth-Heinemann, pp. 807–826, 2019, doi: 10.1016/B978-0-08-100773-0.00017-4.

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