Characterisation of Sewage Sludge and Municipal Solid Waste for Use as Cementitious Materials

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Abstract

Volumes of accumulated solid waste materials of sewage sludge (SS) and municipal solid waste (MSW) in Qatar continue to increase annually with a potentially negative impact on the environment. This paper presents an innovative technology for the production of green cement and advanced construction products from SS and MSW. Chemical composition analyses of the solid waste materials indicated the presence of main oxides available in Portland cement, but at lower contents. The three solid waste materials were incinerated and ground to produce consistent powder materials of similar sizes to Portland cement. The physical and chemical characteristics of the solid waste materials were investigated and compared to that of Portland cement. Paste and mortar mixtures were prepared by replacing 25, 50, and 75% of Portland cement with the different solid waste materials. Solid waste materials were found to influence the fresh properties of concrete, mainly water demand and setting time. Increasing the content of solid waste materials resulted in reduced compressive strength at all tested ages. SS gave the best performance within the solid waste materials investigated. Recommendations are made on the effective use of solid waste materials in various construction applications.

Keywords: Cementitious materials; Compressive strength; Fresh properties; Green construction; Solid waste

1 Introduction

The rapidly developing infrastructure in Qatar, for the 2022 and beyond, consumes large quantities of resources and impacts on the environment. Considering the shortage of quality construction materials in Qatar and waste generation from massive infrastructure projects, there is a need to develop advanced and environment-friendly construction materials to support the government strategy of sustainable development.

Portland cement (PC) production is an energy-intensive process through the heating of limestone and clay together in kilns at elevated temperatures of 1100-1700°C, with each tonne of PC producing a similar amount of CO_2. Cement remains a globally important product with approximately 4.4 billion tonnes produced in 2021, compared to 1.39 billion tonnes in 1995 (Statista, 2022), indicating the growth rate of cement production. Its environmental impact worldwide cannot be ignored, especially with the current technological race against time to reduce greenhouse gas (GHG) emissions, in particular CO_2 emission as the main cause of global warming.

Large quantities of municipal solid waste (MSW) and domestic sewage sludge (SS) are produced every year in Qatar, as seen in Table 1 (PSA, 2019). The production of both MSW and SS increases every year due to population growth, leading to environmental challenges related to the treatment of wastes.

Table 1: Annual production of MSW and SS in Qatar (PSA, 2019)

Year	2013	2014	2015	2016	2017	2018
Population (M)	2,004	2,216	2,438	2,617	2,725	2,760
Domestic solid waste (000s tonnes)	930	1,048	1,096	1,155	1,184	1,313
Sewage sludge (000s tonnes)	27	32	40	42	42	38

MSW is incinerated in an Energy-from-Waste plant in the Domestic Solid Waste Management Centre (DSWMC), under the management of the Ministry of Municipality. The incinerated MSW produces fly ash (FA) and incineration bottom ash (IBA) of approximately 50,000 tonnes per year with the majority of it being IBA. The production of SS biosolids is relatively lower at 45,000 tonnes per annum, and is managed by the Public Works Authority (Ashghal). Current practice in Ashghal is to transfer the SS to the Doha North Sewage Treatment Works (DNSTW), which is equipped with facilities for thermal drying to reduce the volume of SS. The dried SS is produced in pellets, 2-5mm in size, with reduced moisture content of less than 10%. The majority of incinerated MSW and SS waste is sent to landfills with potential impact on the environment.

Landfilling of organic waste without appropriate treatment can pollute the surrounding air, soil, and groundwater environments. When organic landfilled wastes decompose, they create methane gas (CH_4), which is very explosive and flammable. Another significant landfilling concern is leachate management, where heavy metals can become mixed with and contaminate surface water, groundwater and soils. Inappropriate waste disposal can also attract pests and rodents that carry infectious diseases, causing severe environmental health consequences due to pollution and spread of diseases. Dried waste materials, especially fine particles, may be resuspended by wind thereby spread disease and may also increase the risk of fire and explosion (Cai & Zhang, 2013).

This paper presents a methodology for the utilisation of solid waste materials, originating from other sources than construction, for use as cementitious materials in construction applications. Incinerated MSW and SS are used to replace PC in the production of non-structural concrete products, with the double environmental benefits of reducing waste in landfills and carbon emissions from cement production. The work presented is part of a research project funded by the Qatar National Research Fund (QNRF NPRP 12S – 0306 – 1902417) on the “Development of a Novel Technology for Producing Green Cement and Advanced Construction Materials from Solid Waste”. The project is delivered by the Ministry of Environment and Climate Change together with Infrastructure Research & Development (IRD) at the Qatar Science & Technology Park (QSTP) and in collaboration with the Public Works Authority (Ashghal) and stakeholders from the construction industry.

2 Characterisation of Solid Waste Materials

The solid waste materials considered in this investigation are incinerated MSW of fly ash (MSW-FA), incinerated MSW of bottom ash (MSW-IBA), and incinerated sewage sludge ash (SSA). The MSW materials were sourced from the DSWMC, Ministry of Municipality, whereas the SSA material was supplied by Ashghal (DSWMC). The MSW ashes are already incinerated during production at 800-900°C for a duration of 45 minutes. The SS waste material was incinerated in a furnace at the same temperature range of 800-900°C for 2 to 3 hours. The increased incineration time is considered for SSA to minimise the organic content of the material. Fig. 1 shows the incinerated waste materials of MSW-FA, MSW-IBA, and SSA before grinding.

MSW-FA MSW-IBA Incinerated SSA

Fig. 1: Incinerated waste materials used in the investigation (prior to grinding)

The MSW-FA material is collected as a residue of the flue gas, and therefore supplied in a powder form as shown in Fig. 1. The MSW-IBA and SSA waste materials were ground into powder of similar particle size to PC to enhance reactivity as cement substitutes. Grinding was carried out in a dry process using a ball-mill to produce powder, passing 120μm (microns), with homogeneous and consistent appearance.

2.1 Properties of Solid Waste Materials

The grading curves of the solid waste materials together with the grading curve of PC are shown in Fig. 2. The waste materials showed coarser grading than PC, with finer grading of the MSW-FA in comparison to SSA and MSW-IBA. Powder materials passing 75 μm play the greatest part of cement hydration, and the results in Fig. 2 show that more than 90% of the PC particles are passing 75 μm, whereas between 65% and 76% for the solid waste materials.

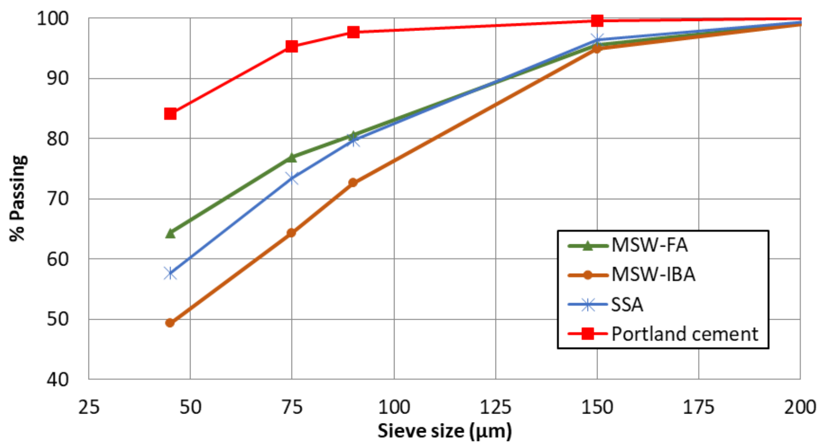

Fig. 2: Grading of waste materials and Portland cement

Table 2 summarises the physical properties of the waste materials and PC powders. PC has the highest specific gravity, followed by the SSA, MSW-IBA and MSW-FA. The Blaine Fineness method was used for the determination of the fineness of powder materials, as per BS EN 196-6 (BSI, 2018).

Despite the finer grading of PC, it gave the lowest surface area of 3130 cm^2/g. The MSW-FA, collected as dust from the hot flue gas, exhibited the highest surface area of 7220 cm^2/g. The difference between the grading and surface area results may be attributed to the surface texture and particle shape of the waste materials. The pH results indicate that all materials are alkalis, with PC exhibiting the highest alkalinity of 12.3 and the lowest of 9.8 for the MSW-IBA.

Table 2: Properties of waste materials and Portland cement

Property	MSW-FA	MSW-IBA	SSA	PC
SG	2.61	2.66	2.99	3.17
Blaine (cm^2/g)	7220	4670	4950	3130
pH	12.3	9.8	11.4	13.0
Chloride (%)	12.59	0.58	0.12	0.09
SO_3 (%)	7.0	0.7	0.9	3.3
LOI[1] (%)	18.0	12.9	2.8	1.6

BS EN 197-1 (BSI, 2011) limits the chloride content of cementitious materials to a maximum of 0.1%. The results in Table 2 show that only PC complies with the chloride requirement, whereas the SSA gave a marginally higher value of 0.12%. MSW-FA exhibited the highest chloride content of 12.59%. BS EN 197-1 also limits the sulfate content (SO_3) to a maximum level of 3.5% and the loss on ignition (LOI) to a maximum of 5.0% by weight of the total binder content. The results in Table 2 show that all the waste materials contain less than 3.5% of SO_3, except the MSW-FA which contains a high sulfate content of 7.0%. Only PC and SSA satisfied the BS EN 197-1 requirement of <5.0% LOI.

The properties of solid waste materials indicate lack of compliance to BS EN 197-1 as cementitious materials, especially for the MSW-FA and MSW-IBA. Despite the chloride and LOI contents, the solid waste materials were investigated further for potential use as cementitious materials in non-structural concrete products. Only SSA has the potential for use in structural concrete applications.

2.2 Chemical Composition

The chemical composition of the solid waste materials is investigated using X-ray fluorescence (XRF) and the results are presented in Table 3. The chemical composition of PC is generally expressed as oxides with main elements of calcium, silica, alumina and iron oxides. PC contains almost 80% of CaO and SiO_2, with less of aluminium oxide (AI_2O_3) and iron oxide (Fe_2O_3). The ratio by mass (CaO) / (SiO_2) shall be not less than 2.0, and the content of magnesium oxide (MgO) shall not exceed 5.0 % by mass (BS EN 197-1, 2011).

Table 3: Chemical composition of waste materials and Portland cement

Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	LOI
MSW-FA	11.24	4.25	1.17	39.16	2.40	5.94	4.97	4.00	1.39	15.01
MSW-IBA	33.84	7.02	10.39	25.60	2.51	0.72	2.26	0.83	2.52	13.32
SSA	20.17	5.70	8.11	28.85	8.87	0.76	1.05	1.78	13.58	2.75
PC	20.49	4.43	3.13	61.78	3.63	3.27	0.21	0.95	0.11	1.58

The main oxide components of the incinerated waste materials are those of CaO, SiO_2, Al_2O_3, Fe_2O_3, similar to that of PC. The SSA is mainly composed of CaO, SiO_2, P_2O5, MgO, and Fe_2O_3, making

[1] Loss on Ignition.

88% of the total oxides. The SSA is low in calcium (CaO) compared to PC, but contains adequate amounts of silica and alumina that could possess pozzolanic reaction. SSA has a high phosphorus content, 13.6 % of P_2O_5, which is not available in other waste materials and PC. MSW-FA has a relatively higher content of CaO and less SiO_2, compared to IBA and SSA. MSW-FA also has the highest content of alkalis (Na_2O and K_2O) and sulfur trioxide (SO_3) compared to IBA and SSA, which are detrimental to the properties of concrete and may limit its use in concrete.

3 Paste And Mortar Mixtures and Properties

The waste materials were used to replace PC at different proportions of 25%, 50%, and 75% by weight of binders and their effects on the fresh and hardened properties of concrete were investigated. Paste specimens were used for investigating the consistency and setting time properties, as per BS EN 196-3 (BSI, 2016). Mortar specimens were prepared in the weight proportions of 1 part of cementitious material: 3 parts of sand: 1 half part of water (water to cement ratio of 0.5), and used for the determination of compressive strength at 2, 7, and 28 days. A summary of the mixtures and test results is given in Table 4.

Table 4: Properties of mixtures prepared with solid waste materials

Mix	Consistency (%)	Setting time (min)		Compressive strength (MPa)			Strength factor ($k=fck_x / fck_{PC}$)
		Initial	Final	2d	7d	28d	
100% PC	26.5	135	210	22.9	36.6	44.8	1
25% FA	27.0	45	75	11.7	20.0	30.4	0.68
50% FA	28.5	30	75	0.0	8.5	17.5	0.39
75% FA	31.0	15	45	0.0	0.0	5.3	0.12
25% IBA	25.0	150	210	13.2	20.6	23.4	0.52
50% IBA	26.0	195	225	3.9	11.3	11.6	0.26
75% IBA	27.5	225	315	0.0	0.0	3.7	0.08
25% SSA	25.0	180	255	21.6	30.6	37.1	0.83
50% SSA	26.0	285	355	11.8	18.2	24.9	0.56
75% SSA	26.5	375	625	0.0	5.3	7.6	0.17

The control mixture was made with 100% PC and labelled (100% PC) in Table 3. Mixtures made with solid waste materials were labelled based on the type of waste materials and percentage of cement replacement. For example, mixture labelled as (25% FA) is made by replacing 25% of PC with MSA-FA, (50% IBA) means replacing 50% of PC with MSW-IBA, and (75% SSA) for replacing 75% of PC with SSA.

Fig. 3: Casting of the fresh mortar prisms

The mortar ingredient materials were mixed mechanically using an electrical mixer for 3 minutes and cast into prism moulds of the dimensions of 40x40x160mm, as shown in Fig. 3. The fresh mortars, inside their moulds, were covered with wet hessian and polyethylene sheets for 24 hours and demoulded on the following day. Curing of the mortars mixtures was made in a water tank maintained at 20±2°C until testing.

3.1 Paste Results

The paste specimens are tested for consistency and setting time and the results are given in Table 3. The consistency test determines the amount of water required for the complete hydration of cement particles. The consistency of PC is 26.5% and the use of solid waste materials resulted is similar or higher consistency values. Increasing the FA content from 25% to 75% increased the consistency to 27% to 31%, respectively. FA had the highest particles surface area, almost double of PC, and would require more water to achieve the standard consistency. The IBA and SSA mixture had marginal effects on the standard consistency, compared to PC.

The setting time results are also given in Table 3. The initial and final setting times of the 100% PC are 135 and 210 minutes, respectively. The use of MSW-FA significantly reduced the setting time compared to PC, with high replacement level results in faster setting. The lowest initial setting of 15 minutes and final setting of 45 minutes are achieved for the 75% FA mixture. In contrast, the use of MSW-IBA and SSA delayed the setting time. Increasing SSA replacement level resulted in a delay in both initial and final setting times. Replacing 75% of PC with SSA increased the initial and final setting times to 375 and 625 minutes, respectively, almost triple the values obtained for the control 100% PC. Similar findings on the retarding effect of SSA have been reported by previous studies due to the presence of phosphorus oxide (Cyr, 2007; Piasta & Lukawska, 2016). The delay in setting times may be an advantage in hot regions for use in specific applications.

3.2 Mortar Results

Compressive strength testing was conducted at the ages of 2, 7, and 28 days on the different mortar mixtures, and the results are given in Table 3 and also presented in Fig. 4. Table 3 also provides the 28-day strength reduction factor (k) defined as the ratio of compressive strength of the mixture made with different proportions of waste materials in relation to the compressive strength of the 100% PC mortar. The PC mortar attained compressive strength values of 22.9 MPa at 2 days (≥20 MPa) and 44.8 MPa at 28 days (≥42.5 MPa), and therefore classified as a Strength Class 42.5 R according to BS EN 197-1. The use of waste materials, as cement replacement, resulted in lower compressive strength, and the strength reduction is proportional to the replacement level.

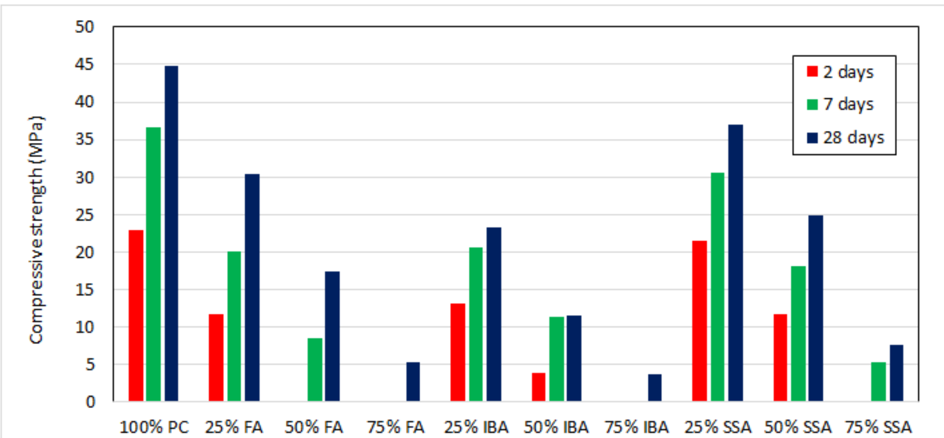

Fig. 4: Compressive strength of the mortar mixtures

Replacing 25%, 50% and 75% of PC with FA reduced the 28-day compressive strength to 30.4, 17.5, and 5.3 MPa, respectively. A strength reduction of 32%, 61%, and 88%, respectively. In fact, the 75% FA mixture did not attain any measurable strength at 2 and 7 days, and only achieved 5.3 MPa at 28 days. Similar trend to the FA was observed for the IBA mortars, but with lower compressive strength values at all tested ages. The 28-days compressive strength of the 25% IBA was 23.4 MPa, a reduction of 48% compared to the 100% PC. The 50% IBA and 75% IBA mixtures gave 28-day strength values of 11.7 and 3.7 MPA, reduction of 74% and 92%, respectively. Similar to the FA mixture, the 75% IBA mortar did not achieve any measurable strength at the ages of 2 and 7 days, and only reached 3.7 MPa at 28 days.

The best compressive strength results among the investigated waste materials are found in the 25% SSA. The inclusion of SSA reduced the compressive strength but at a lower magnitude than the FA and IBA materials. The 25%, 50%, and 75% SSA mortar mixtures exhibited 28-day strength values of 37.1, 30.6, and 21.6 MPa, a loss of 17 %, 32 %, and 52 % compared to 100% PC, respectively. In other words, the SSA mixtures attained 48% to 83% of the 28-day compressive strength of 100% PC at the different replacement levels of 25 to 75%., compared to 12 to 68% for the FA and 8 to 52% for the IBA.

The use of waste materials in construction has the double environmental benefits of reducing waste sent to landfills as well as the carbon emission associated with the production of PC. The new development of "Green Cement" is towards the achievement of a substantial reduction in CO_2 emission while transforming waste from landfills to useful construction products. SSA was found to be the most viable material that resulted in moderate reduction in strength properties, and better performance compared to the other two solid waste materials. Its physical and chemical properties suggest that SSA could be blended with other cementitious materials to satisfy most of the requirements of a cementitious binder for structural and non-structural concrete applications. SSA retardation of the setting time may be an advantage in hot countries, especially in applications that require longer setting time. Replacing 50 to 75% of PC with SSA will produce concrete with 28-day strength of 7 to 25 MPa, which could be widely used in non-structural concrete applications as green products with less impact on the environment. Further work is planned to use different activation techniques of SSA to enable its utilisation in a range of construction application.

4 Conclusion

Three solid waste materials of municipal solid waste (MSW) of fly ash (FA) and incineration bottom ash (IBA) and sewage sludge ash (SSA) were considered in this investigation for use as cement replacement materials. The solid waste materials contain similar oxide components to PC but failed to comply with BS EN 197-1, especially for the MSW-FA and MSW-IBA in terms of salt and LOI contents. Only SSA possessed any potential for use in structural concrete applications.

The solid waste materials were used to replace PC at different levels of 25, 50, and 75%, by weight of binder, for the development of paste and mortar mixtures. FA increased the water demand of the paste whereas the IBA and SSA had marginal effect on consistency. FA also accelerated the initial and final setting whereas SSA and IBA delayed the setting time. The retarding effect was more pronounced for the SSA with its high content of phosphorus oxide. The use of solid waste materials reduced the compressive strength of mortars, and the reduction was proportional to the replacement level. Within the investigated solid waste materials, SSA exhibited the best performance in terms of water demand and compressive strength when compared to MSW-FA and MSW-IBA materials. Non-structural concrete products of 7 to 25 MPa could be achieved by replacing 50 to 75% of Portland cement with SSA.

The work conducted in this investigation is limited to small patches received from two recycling plants in Qatar for the processing of domestic municipal and sewer waste materials. Variations of the processed waste materials may affect the derived conclusions. Further work is currently being undertaken for assessing the variability of waste materials produced at different ages and also investigating the use of different techniques for the activation of solid waste materials to develop innovative concrete products.

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