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Citation for published version (APA):
Gao, X., Yu, Q. L. Q., Li, X. S., & Yuan, Y. (2020). Assessing the modification efficiency of waste glass powder in hydraulic construction materials. *Construction and Building Materials, 263*, [120111].
https://doi.org/10.1016/j.conbuildmat.2020.120111

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DOI:
10.1016/j.conbuildmat.2020.120111

Document status and date:
Published: 01/01/2020

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
- The final author version and the galley proof are versions of the publication after peer review.
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Download date: 04. Mar. 2021
Assessing the modification efficiency of waste glass powder in hydraulic construction materials

X. Gao a, Qingliang Yu b,c,⇑, X.S. Li d, Yuliang Yuan e

a School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, PR China
b School of Civil Engineering, Wuhan University, 430072 Wuhan, PR China
c Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
d State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, PR China
e Henan Water & Power Engineering Consulting Co., Ltd., 450016 Zhengzhou, PR China

HIGHLIGHTS

- Waste glass enhances workability of AAM and Portland cement system.
- Waste glass shows comparable reactivity as silica fume in AAM.
- Waste glass promotes polymerization degree in AAM.
- Waste glass improves the strength of alkali-activated binder.

ABSTRACT

In this paper, the effects of waste glass powder on reaction kinetics, gel characteristics, as well as workability and mechanical property of two typical binding systems: Portland cement system and alkali activation system, are investigated. The commercial silica fume was used as a comparative supplementary cementitious material. The results show that waste glass incorporation improves the workability, while silica fume presents an obvious negative effect. Both waste glass powder and silica fume delay the early age reaction to some degree, but the reduction is less significant for waste glass. The addition of waste glass shows limited effect on the typical gel structure in Portland cement system; while in alkali activated system, silica fume incorporation results in more polymerized Si–O structure than waste glass. Thermal analysis indicates that waste glass powder exhibits relatively lower reactivity than silica fume in Portland cement system, but very similar reactivity in alkali activated system. Mixes containing waste glass show comparable but slightly lower compressive strength than the ones with silica fume addition, but a better balance between performance and cost is achieved. The microstructure characterizations further confirm the beneficial effect of waste glass powder in producing cementitious binding materials.

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1. Introduction

A simple and commonly used approach to handle the solid wastes is landfill, while landfill of those non-degradable wastes shows negative impacts on resource management and sustainable development. Waste glass is one of these wastes that sometimes end by landfilling; the collected waste glass usually presents large variations in type and chemical compositions, which brings difficulty in the quality control and recycling efficiency of glass production, and up to about 30% of the waste glass is not recycled in Europe as a result [1]. Meanwhile, growing interests have been paid to reusing waste materials in construction and building materials due to the benefits of reducing the consumption of natural resources, the overall costs and relieving the pressure of landfill [2,3]. The possibility of reusing waste glass in construction and building industry has been investigated in previous studies [4–8], and two application directions can be classified according to the particle size distributions: aggregates and binder components. Benefits from the cooling process of glass production, amorphous silica that exhibits potential reactivity is resulted. Coarse fractions of the waste glass are reported to show the risk of alkali silica reaction (ASR), resulting in related degradations [9–11], while suitable
amount of waste glass aggregates or fine glass fractions has reported to show limited effect on cement chemistry and ASR related expansions [12–17].

The reuse of waste glass as a binder substitute in Portland cement systems has been widely studied, because the amorphous silica enriched glass fines may show similar pozzolanic characteristics as other common supplementary cementitious materials (SCMs) such as fly ash, slag, metakaolin and silica fume; those materials are well known to modify the macro performances of concrete and reduce the cement consumption. Furthermore, the utilization of waste glass powder provides additional source of the SCMs that also show advantages in availability, costs and waste management. Fine glass powders are reported to exhibit high pozzolanic reactivity, and the reactivity is positively related to the fineness, 20% replacement shows an increased strength and even reduced expansion [18]. A glass powder replacement up to 30% was confirmed to be suitable of achieving acceptable mechanical properties without detrimental effects on drying shrinkage, ASR and chloride penetration [19]. The pozzolanic reactivity of glass powder and its beneficial effect regarding some important engineered properties are also reported in previous studies [14,20–22]. Micro scale analysis showed that limited amount of sodium can be released from the glass powder; glass powder addition showed higher chemical bond water content and accelerated hydration process Alite (C3S) compared to the plain paste [23,24], as well as modified microstructures [25]. Those studies provide some basis for understanding the role of glass powder in Portland cement systems and suggest a promising application potential of this alternative binding material.

On the other hand, increasing attentions were also paid to utilizing this waste in alkali activated materials (AAMs), AAM is an alternative binder system that is usually prepared by mixing amorphous Ca, Si and Al contained solids together with alkali activators [26,27].

The commonly used raw materials include industrial by-products such as blast furnace slag and fly ash, solid wastes like red mud and coal gangue, natural materials for instance pozzolans and calcined clay [28,29]. This binder system shows advantages in energy costs and carbon emissions, as well as excellent mechanical properties, durability and sometimes functional properties including thermal resistance, toxic ion immobilization [30–35]. The main elements in waste glass are silica, sodium and calcium, which are also the input components of alkali activation [36]; therefore, the use of waste glass in alkali activated systems as alternative reactive phase can result in a more sustainable product with further reduced environmental impacts. Waste glass has been reported to be suitable as an alternative silica source in preparing activators to replace commercial sodium silicate [37–40], as well as supplementary binder materials to replace solid raw materials [41–43].

Previous researches have shown the application potential of waste glass powder in two commonly used binder systems, while in order to apply this waste material in a specific mix design with tailored properties, a more detailed understanding about its modification mechanism and efficiency in different binding systems is still necessary. Also, to what extent it can be used to replace the already existing supplementary binder materials is not clear. The objective of this study is to investigate the reaction mechanisms and identifying the workability, mechanical property and microstructure of waste glass powder in two different binding systems: alkali activated materials and cementitious materials. Another silicate enriched supplementary binder, silica fume, was also used as an alternative binder to compare its reactivity with waste glass powder. For alkali activated binders, blast furnace slag is a commonly accepted raw material that would ends in excellent mechanical properties and durability, and usually presents comparable performances to Portland cement, therefore it is selected as the representative precursor for alkali activated system. The reaction kinetics and gel composition were characterized by using isothermal calorimeter, X-ray diffraction, Fourier transform infrared spectroscopy and Thermo-gravimetric; also the flowability and mechanical properties were evaluated. It was indicated that compared to the high effective commercial silica fume, waste glass powder exhibits slightly lower reactivity in Portland cement systems, while presents improved workability and similar reaction potential in alkali activated systems. Thus, from the aspects of pozzolanic reactivity, microstructure, workability and mechanical property, it shows the potential to be reused as a green substitute with high efficiency in producing hydraulic construction materials.

2. Experiment

2.1. Materials

The raw materials used for alkali activation is a commercial granulated blast furnace slag. A 42.5 type I cement according to EN 197–1 was used as a representative binder for Portland cement systems. Other applied powder materials are ground waste glass from the crushed bottles, the bottles were obtained from urban daily wastes, they were collected, cleaned and then ground to powder. The colour of the bottles is not considered in the selection process because of its extremely limited influence on chemical composition and potential reactivity. A commercial silica fume is used as a representative silicate enriched supplementary cementitious materials (SCMs). Besides, CEN standard sand was used as fine aggregates for preparing the mortar samples. The major chemical composition of the powder materials is presented in Table 1. The particle size distributions of all applied solids are presented in Fig. 1. A mixture of sodium hydroxide and commercial waterglass was used to prepare the activator solution. The waterglass, namely sodium silicate solution, consists of 27.69% SiO₂, 8.39% Na₂O and 63.92% H₂O by mass. The target activator modulus (SiO₂ to Na₂O ratio) was obtained by mixing suitable amount of sodium hydroxide with sodium silicate solution.

2.2. Sample preparation

For both alkali activated materials and cementitious materials, a fixed water to binder ratio of 0.45, namely a constant water dosage is applied for all mixes. For alkali activated slag, an equivalent sodium oxide (Na₂O) content of 5% by mass of the binder and an activator modulus of 1.4 are chosen based on our previous experiences (Gao et al., 2015; Gao et al., 2017). It should be noted that the total water content is alkali activated materials includes both the additional added water and the water that within the sodium silicate solution, while the Portland cement-based samples are prepared by mixing solid powders with admixed distilled water. Waste glass powder replacement up to 20% with an interval of 10% (by mass of the initial binder) was used in both alkali activated and Portland cement systems, silica fume with the same replacement levels are also used in the two binding systems. A total binder dosage and a binder/aggregation ratio of 1/3 are applied for all mortar mixes. The detailed mix proportions are listed in Table 2.

2.3. Testing methods

The slump flows of all mixtures were measured according to EN 1015-3. The early age heat release was evaluated by a TAM Air isothermal calorimeter, 6 g of distilled water was used as the standard reference, and the measurements were performed for 72 h with a fixed temperature of 20 °C. The XRD analysis was carried out using a Bruker 2D phase instrument, with a cobalt tube and 2θ range from 5° to 60° and a step size of 0.02°. FTIR analyses were conducted in a Varian 3100 instrument with wavenumbers from 4000 to 600 cm⁻¹. TG analyses were conducted by using a STA 449 F1 instrument, with a heating rate of 5 °C/min up to 1000 °C, N₂ was used as the flow gas and the flow speed was 20 ml/min. The samples for compressive strength tests were cured under 20 °C and RH of 95 ± 3%, the recorded strength value was an average of two tests. Besides, samples for XRD, FTIR and TG analysis were collected from paste mixtures, and ground to pass a 300 μm sieve before testing.

3. Results and discussion

3.1. Flowability

The slump flows of the fresh mortars containing different levels of waste glass powder and silica fume, in both alkali activated system and Portland cement system, are depicted in Fig. 2. As mentioned in previous sections, a constant water dosage is applied to
all mixtures in this study and no superplasticizer is used, the shifts of workability are then due to the replacement of either waste glass powder or silica fume. The data briefly illustrate the effect of powder addition and binder type on workability. It can be observed that for a constant powder replacement, the mixtures based on alkali activated materials exhibit higher slump flows than those of Portland cement. The slump flow of alkali activated slag without alternative powder addition is 27.2 cm, which is higher than that of Portland cement (23.5 cm). It is generally believed that the water demand and the resulting flowability are directly related to particle size and surface area of the solids; however, differences may show when different binder systems are applied. As shown in Fig. 1 that although slag presents a finer particle size than Portland cement, the derived fresh mortar still presents a higher value slump flow. It is suggested that the sodium silicate-based activator changes rheological characteristics of the fresh mixes. When glass powder was applied, the slump flow slightly increases with the increasing replacement level in alkali activated slag. The glass powder with the replacement of 20% increases the slump flow from 27.2 to 29.1 cm (by around 7%).

Similar tendency is also observed in Portland cement systems, glass powder replacement up to 20% results in an increased slump flow from 23.5 to 26.1 cm. Contrary to the effect of glass powder, the addition of silica fume leads to a significant reduction of flowability in both Portland cement and alkali activated systems. For instance, the slump flow is reduced from 27.2 to 20.4 cm (by 25%) when 20% slag is replaced by silica fume, and a reduction from 23.5 to 14.3 cm in cement based mixtures. For a fixed binder system, the shifts in flowability are attributed to the particle shape, surface area and porosity of the applied solids, thus compared to the commonly used silica enriched additive: silica fume, glass powder exhibits an advantage in terms of the workability, and show differences in powder morphology, the beneficial effect of waste glass on flowability was also reported in previous studies [44–46]. It should be noticed that there is a difference between the particle sizes of silica fume and waste glass powder, while within this very close PSD range, it is still believed that the morphology plays an important role on workability.

### 3.2. Reaction kinetics

The normalized heat flow and heat release of alkali activated slag with glass powder and silica fume addition within the first 72 h are illustrated in Fig. 3. Two typical heat release peaks are usually presented in alkali activated slag: an initial peak due to the initial dissolution; and an acceleration peak with relatively low intensity owning to the reaction process [47–49]. It can be observed from Fig. 3(a) that the reference mixture shows a main heat release peak located at around 14.6 h with a peak intensity of 1.60 mW/g, and the induction period is between around 5–10 h. As the glass powder replacement increases to 10% and 20%, the location of main reaction peak presents a delay to 15.9 and 17.3 h with slightly increased peak intensity, and the induction period shows a delay up to around 1.2 h. The slightly delayed location of the main reaction peak suggests that the amorphous phases within the glass powder exhibit lower reactivity than slag under alkali environment. In terms of the silica fume, the same replacement level results in a more significant delay of the main reaction peak and an evident reduction of the peak intensity compared to the glass powder. The peak intensity of mixtures with 10% and 20% silica fume are 11.3% and 32.3% less than the relating ones with the same amount of glass powder; the peak location also shows a delay of 2.3 and 8.0 h, respectively. It indirectly verifies that the glass powder presents a much higher reactivity than silica fume in alkali activated systems. As for the total heat release shown in Fig. 3(b), alkali activated slag without additives presents

### Table 1

| Oxides (wt%) | OPC | GGBS | WG | SF |
|--------------|-----|------|----|----|
| SiO₂         | 19.82 | 34.44 | 69.51 | 93.06 |
| Al₂O₃        | 5.36  | 13.31 | 0.91 | – |
| CaO          | 63.54 | 37.42 | 10.52 | 0.89 |
| MgO          | 1.27  | 9.89  | 1.28 | 0.69 |
| Fe₂O₃        | 7.72  | 0.47  | 0.30 | 2.06 |
| Na₂O         | –     | 0.34  | 16.38 | 0.63 |
| K₂O          | 0.09  | 0.47  | 0.69 | 1.15 |
| SO₃          | 2.86  | 1.23  | 0.06 | 1.28 |
| LOI          | 1.82  | 1.65  | 0.02 | 0.24 |

### Table 2

Mix proportions of alkali activated materials and cement based materials.

| Sample  | Binders | Liquids | Glass powder | Silica fume | Fine aggr. |
|---------|---------|---------|--------------|-------------|------------|
| OPC     | 0       | 100     | 0            | 0           | 45         | 0          | 0          | 300 |
| OPC-10GP| 0       | 90      | 0            | 0           | 45         | 10         | 0          | 0   |
| OPC-20GP| 0       | 80      | 0            | 0           | 45         | 20         | 0          | 0   |
| OPC-10SF| 0       | 90      | 0            | 0           | 45         | 10         | 0          | 0   |
| OPC-20SF| 0       | 80      | 0            | 0           | 45         | 20         | 0          | 0   |
| AAM     | 100     | 0       | 24.4         | 3.8         | 29.4       | 0          | 0          | 0   |
| AAM-10GP| 90      | 0       | 24.4         | 3.8         | 29.4       | 10         | 0          | 0   |
| AAM-20GP| 80      | 0       | 24.4         | 3.8         | 29.4       | 20         | 0          | 0   |
| AAM-10SF| 90      | 0       | 24.4         | 3.8         | 29.4       | 0          | 10         | 0   |
| AAM-20SF| 80      | 0       | 24.4         | 3.8         | 29.4       | 0          | 20         | 0   |
the lowest heat of 158 J/g until the testing age of 72 h. The cumulative heat release increases as the increase of powder replacement in the system, indicating that both glass powder and silica fume show a potential reactivity in alkali solutions. Besides, although the addition of glass powder and silica fume show significant difference in heat flow, the overall heat release remain similar for a constant dosage, indicating their differences in reaction mechanisms and reactivity, but similar promoting effect on the overall reaction process.

Fig. 4 illustrates the effect of silica fume and waste glass powder on early age hydration in Portland cement systems. The hydration process of Portland cement presents similar typical four stages as alkali activated materials, while with differences mainly regarding the induction and acceleration stage. This is attributed to the different hydration characteristics of the multiple phases such as C₃A, C₃S, C₂S and C₄AF within the clinkers. It can be seen that other than alkali activated slag, the addition of additives show very limited influence on the induction stage; due to the fact that this process is mainly controlled by the ettringite formation [50,51], while several factors such as alkali concentration, reactivity of starting materials show an effect on this stage in alkali activated system [52]. For mixtures without additives, the main reaction peak is located at around 14.7 h with a peak intensity of 1.54 mW/g, both values are similar to alkali activated pure slag. Different from the role of glass powder in alkali activated system, the addition of glass powder leads to the shift of main reaction peak earlier times with reduced peak intensity, indicating an acceleration effect. It also results in a more significant heat release at around 25 h, which is related to the formation of A²f₅ phases [53]. For the same replacement level, the addition of silica fume slightly retards the main reaction peak up to around 1 h with a more significant reduction of peak intensity, and exhibits limited effect on the A²f₅ related reactions. The cumulative heat release results in Fig. 4(b) shows that contrary to the alkali activated system, the addition of glass powder and silica fume reduces the heat release of the original binder, indicating reduced binder reactivity. This is because that in alkali activated systems, any amorphous silica can be regarded as the precursors; while in Portland cement system, the main reaction process is only controlled by the cement clinkers.

3.3. Fourier transform infrared spectroscopy

Fig. 5 shows the spectra of the raw materials. The original slag presents a absorption band between 850 and 950 cm⁻¹, attributing to the stretching of Si–O–T bonds, where “T” = Si or Al units. Another absorption band at about 670 cm⁻¹ is assigned to the vibration of tetrahedral T–O [54]. As for the Portland cement, an absorption peak at 875 cm⁻¹ and a broad band that centered at around 935 cm⁻¹ indicates the presence of asymmetric stretching T–O bonds. A previous study concluded that the location of the T–O band is related to its Si/Al ratios and polymerization degree. The replacement of Si by Al results in a reduced T–O angle and smaller bond force, shifting the infrared signal to lower frequency [55]. The absorption band at about 1130 and 1460 cm⁻¹ in cement are due to the vibration of bridge Si–O–T and O–C–O bonds [56]. Waste glass powder and silica fume exhibits similar bond locations, such as the vibration of T–O bonds at 770 and 800 cm⁻¹, bridge Si–O–T bonds at around 1100 and 1210 cm⁻¹, as well as the main absorption bonds at 990 and 1070 cm⁻¹. The generally higher location of each specific bond in silica fume indicates a higher polymerization degree of the Si–O structures.
Fig. 6 depicts the infrared spectra of mixtures upon activation. Portland cement-based samples show a main absorption band at around 950 cm\(^{-1}\), which is attributed to the asymmetric stretching vibration of a terminal Si–O bond. The location of this band is higher than the relating ones in the original cement, indicating a slightly higher crosslinking structure of the hydrated C-S-H gels than the clinkers. Two types of tetrahedral T–O bonds are observed at around 875 and 820 cm\(^{-1}\), the former one is from the original Portland cement, as can be seen that a sharp peak at the same location is shown in the starting material; while it is difficult to identify whether the latter one is newly formed since the cement clinker shows a broad and poorly defined shoulder in the similar location range. The broad band at around 1130 cm\(^{-1}\) in cement slightly shifted to 1120 cm\(^{-1}\) with increased intensity, indicating an increased amount of the bridge T–O–Si bonds during hydration. The absorption band at about 1420 and 1640 cm\(^{-1}\) indicates the strong presence of O–C–O bonds and chemical bond water within the hydration products. The location of the typical Si–O–T bonds in the hydration products remain fixed with the addition of glass powder or silica fume, while the intensity of the main terminal Si–O bonds at around 950 cm\(^{-1}\) show a increment. This indicates their addition shows limited effect of on the characteristics of the original Si–O structures, but increases the total amount of Si–O bonds in the reaction products.

The infrared spectra of alkali activated slag based mixes present some differences in terms of the Si–O bond composition, due to the differences in the starting precursors and reaction mechanisms. The main absorption band is located at around 950 cm\(^{-1}\), which has the same location as the one in Portland cement. It is also reported that the tobermorite-like chain structured C-S-H type gels from alkali activated slag share a similar structure with the ones in Portland cement, and show differences in Ca/Si ratio and Al content. A small shoulder at around 890 cm\(^{-1}\) is shown in alkali activated slag and slag-glass powder blends, which is a terminal Si–O bond with less crosslink or more Al replacement than the main Si–O bond. The terminal Si–O bond at 820 cm\(^{-1}\), 875 cm\(^{-1}\) and the bridge Si–O bond at 1130 cm\(^{-1}\) in Portland cement based samples are no longer significant in those alkali activated slag and slag-glass powder blends. Different from the effect of glass powder, the addition of silica fume show an absorption band at 875 cm\(^{-1}\) instead of 890 cm\(^{-1}\). The presence of a bridge Si–O bond at
1130 cm$^{-1}$ and the shift of main absorption band from around 950 to 970 cm$^{-1}$ indicate that a more polymerized structure is resulted.

3.4. X-ray diffraction

The X-ray diffraction patterns of the starting materials are shown in Fig. 7. The Portland cement show large amount of C$_3$S/C$_2$S, together with C$_2$A, C$_3$AF, gypsum, and limited amount of quartz. The original slag and glass powder are mainly amorphous without the presence of significant crystalline phases. The slag shows a peak hump between 30 and 40$^\circ$, while a wider hump range can be observed in the waste glass from around 20–40$^\circ$. Regarding the silica fume, a broad hump with relatively high intensity is shown between about 20 and 30$^\circ$, as well as limited amount of crystalline phases such as quartz and hematite. The different hump characters indicate the differences of amorphous structures within the starting materials.

The XRD patterns of the reaction products are depicted in Fig. 8. As can be seen that the hydration/reaction products in Portland cement and alkali activated systems present distinguished characteristics, and the addition of glass powder and silica fume plays different role in different binder systems. Two evident crystalline peaks can be observed in Portland cement based mixtures: Ettringite and Portlandite, which are typical hydration products due to the presence of sulfates and considerable amount of calcium [53]. Small amount of unreacted clinkers can be observed; especially the non-Al involved ones such as C$_3$S and C$_2$S. The main hydration product: C-S-H type gels, presents a sharp peak at around 34$^\circ$ (in Cobalt tube, as described in Section 2.3). The addition of glass powder results in a reduced peak intensity of Portlandite, indicating a reduced amount of it within the hydration products due to the well-known secondary hydration process. The same replacement of silica fume instead of glass powder leads to a more significant reduction of Portlandite peak intensity, which reveals that the glass powder presents a lower pozzolanic reactivity than silica fume. As for the alkali activated materials, the main reaction product is a poorly crystalline C-S-H type gel. Compared to the C-S-H gels from Portland cement system, it has the same peak location while with much lower peak intensity, this gel is also known to have a higher Al content and a lower Ca/Si ratios [57].

Furthermore, when excluding the mass loss of Portlandite, mixes with glass powder or silica fume present a higher content modification efficiencies in Portland cement system as supplementary binders that contribute to the secondary reaction; while exhibit similar reaction mechanism in alkali activated system, as starting precursors that change the overall Si content in the system, their modification efficiency in alkali activated systems will be further discussed in the following thermal analysis section.

3.5. Thermo-gravimetry

The TG/DTG results of mixes with different starting compositions and binder systems are shown in Fig. 9. In order to perform a clear view focusing on the mass loss of the reacted gels, the mass at 100 $^\circ$C is calculated as the starting mass of 100%. Fig. 9(a) depicts the mass losses of Portland cement based mixtures between 100 and 1000 $^\circ$C. All mixtures exhibit similar characteristics of mass loss within the tested temperature range, including a continuous mass reduction before around 400 $^\circ$C, a significant mass loss between around 400 and 480 $^\circ$C, and a less evident one between 600 and 700 $^\circ$C; then the mass loss remains stable and limited until 1000 $^\circ$C. In relation with the abrupt mass losses in the TG results, the corresponding DTG curves indicate the presence of three phases within the hydration products: AFm, Portlandite and Carbonates. It should be noticed that the gradual decomposition of the C-S-H gels and resulting loss of bound water also take place within this temperature range.

The DTG curves reveal that the addition of glass powder shows limited effect on the content of AFm and Carbonates, while reduces the Portlandite content to some extent. The addition of silica fume shows a further reduction of Portlandite, which is in consistent with the XRD results. The mass loss between 370 and 450 $^\circ$C, that mainly assigning to the loss of Portlandite according to the DTG curves, is around 4.1% for mixes with plain Portland cement. When replacing the OPC by glass powder with a dosage of 20%, this value reduces to about 3.4%, and the same replacement level of silica fume results in a higher reduction of around 2.4%, indicating a higher efficiency in terms of the secondary hydration. It should be noted that silica fume is commonly accepted as a commercial high efficient SCM, while the glass powder is an industrial solid waste. Therefore, when evaluating and comparing their effects on micro or macro level, their environmental impacts and costs should be considered together with the pozzolanic efficiency. Additionally, when excluding the mass loss of Portlandite, mixtures with glass powder or silica fume present a higher content...
of chemical bound water, confirming again the benefits of secondary hydration.

Concerning the alkali activated systems, as can be seen in Fig. 9 (b) that all mixes present a relatively evident mass loss till around 300 °C, and then become stable until 1000 °C without significantly abrupt mass losses. This is in line with the XRD results that the reaction products are mainly amorphous gels without well-defined crystalline phases. Similar to the case of Portland cement system, the addition of glass powder increases the total mass loss (between 100 and 1000 °C) from around 7.6% to 8.7%, mainly attributing to the increased bound water, while the addition of silica fume exhibits a higher total mass loss of 9.4%. The DTG curves show a slight shoulder at around 330 °C, which can be assigned to the mass loss of Hydrotalcite. The presence of this phase is commonly reported in alkali activated materials [58,59], the minor amount together with the poorly crystalline nature make it almost undetectable from the XRD analysis in this study. To summarize, the TG/DTG analysis provides additional information in evaluating the effect of glass powder in two different binder systems, modifications in bound water and phase changes are identified. Quantitative comparison made with silica fume gives a clear view on the modification efficiency of glass powder, which can also be linked to the results of other testing methods.

3.6. Compressive strength

The 7 and 28 d compressive strengths of all mixtures are presented in Fig. 10. The strength variations are lower than 8% in most cases, therefore the recorded strengths can be used as effective values. In Portland cement-based mixes, the reference sample reaches a 7 d strength of 35.3 MPa and 28 d strength of around 46.2 MPa. The addition of glass powder up to 20% shows slight strength increment at both 7 and 28 d, as can be seen that the strength is increased by 1.3 MPa after 7 d of curing and 2.6 MPa at 28 d. While in terms of the silica fume, its incorporation up to 20% results in a more significant increase of strength compared to glass powder, especially at the dosage of 20%. For instance, compared to the reference, the 7 and 28 d strength is increased by 4.4 MPa and 8.3 MPa respectively, when 20% silica fume is added, and the highest 28 d strength reaches 54.5 MPa. Compared to the effect of glass powder and silica fume, this study reveals that the reuse of glass powder at least shows no negative effect on mechanical property, namely replacing Portland cement with 20% glass powder would result in a similar level of strength. Although the commercialized silica fume shows better modification efficiency in terms of strength, its high purity of amorphous silica and high price should also be taken into consideration; while the glass powder is only an industrial waste with less silica content (see Table 1) and lower intensity of amorphous phases (see the XRD pattern in Fig. 7).

As for the alkali activated materials, a higher compressive strength in general is clearly shown, partly because of the nature of the reacted gels and the nature of lack of calcium hydroxide within the reaction products. The reference sample presents 7 d strength of 56.8 MPa and 28 d strength of 63.8 MPa, which are much higher than the corresponding Portland cement-based mixes. The effects of glass powder and silica fume on strength show a similar tendency as the case in Portland cement binders. For a constant replacement level, the addition of silica fume leads to a higher increase of strength than glass powder at both 7 and 28 d. The silica fume/glass powder dosage up to 20% shows beneficial
In order to provide a more clear view on the micro/macro modifications of waste glass powder and silica fume in two different binding systems, there influences on the above discussed issues are summarized and shown in Table 3. Their influences on alkali activated binding system and Portland cement system are listed separately, as well as the reference values. It should be mentioned that for each discussed issue, label “Ref” refers to the tested value of samples produced with only Portland cement (OPC) or alkali activated slag (AAM), while the percentage values are attributed to their relative shifts compared to the “Ref” value, increment is marked with “+” and reduction is noticed as “−”.

As for the 28 d compressive strength, this table clearly depicts that for the same replacement level, silica fume exhibits an obviously higher contribution on mechanical property than glass powder, this can be attributed to the higher intrinsic pozzolanic reactivity of silica fume than waste glass powder, therefore more reactive silicate groups can be participated into the reaction process and generate more reaction products. The strength results and the proposed reactivity difference between the two additives in Portland cement system can be well explained by the CH contents, since a fixed replacement level results in more consumed CH and therefore higher strength in silica fume added mixtures.

Table 3 also shows that the effect of these two additives on strength is more significant in Portland cement system, it can be partly explained by the CH contents listed in the table, where both silica fume and waste glass powder modify the compressive strength by consuming the portlandite in Portland cement system, but only providing additional reactive groups in alkali activated systems. Concerning the slump flow results, the contrarily effect of silica fume and waste glass powder is clearly presented, the waste glass powder benefits the workability whilst silica fume show a negative effect; it is also clear that the effect of additives on slump flow is more obvious in Portland cement system. The difference in workability can be partly explained by the fineness of these two applied powders, as can be seen from Fig. 1 that the D50 of silica fume is around 11 μm, while this value is almost two times larger for waste glass (about 20 μm). Contrarily effect between silica fume and waste glass is also shown regarding the location of the maximum hydration heat release, in Portland cement system, the waste glass powder accelerates the early hydration while silica fume slightly inhibits the reaction; but in alkali activated system, opposite results can be observed. It indicates that these two additives work differently during the early age hydration in different binding systems. The total hydration heat release up to 72 h indicates different effects of additives in different binding systems, the binder replacement results in a reduction of total heat release in Portland cement system, while a increment in alkali activated systems. This can be attributed to their different hydration/reaction mechanisms, which can be found in the phase identifications shown in Sections 3.3 to 3.5. The generally unchanged main Si–O bond location indicates that the addition of either waste glass or silica fume exhibit limited effect on the main gel structure, and it is suggested that the slightly shifted Si–O signal is due to the overlap of unreacted silica fume and hydration products.

4. Conclusions

This study evaluates the influences of waste glass powder as a partial replacement of the binder in alkali activation and Portland cement systems. The commonly known high effective mineral additive, commercial silica fume, was used as a comparative reference. The results show that different from the effect of silica fume, the addition of waste glass powder slightly enhances the workability, and presents different early age hydration/reaction characteristics. Silica fume exhibits a higher pozzolanic reactivity than glass powder in Portland cement system, while interestingly presents very similar reactivity in alkali activated system according to the thermal analysis, it may demonstrate that the waste glass powder can be reused as a material with high-ended value in alkali activated systems, the increased polymerization degree of the Si–O bond caused by glass powder in alkali activated system can be a possible indication of its unique contribution. Strength results show that waste glass addition increases the compressive strength in general, and silica fume incorporated mixes present a relatively higher increment. It is further concluded that appropriate dosages of silica fume and waste glass powder need to be comprehensively determined based on a series of technical requirements including workability, mechanical properties and durability considering the engineering applications.
Acknowledgements

This research was supported by the Fundamental Research Funds for the Central Universities (WUT: 193106004), China Scholarship Council and the Department of the Built Environment at Eindhoven University of Technology.

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