Review

Recent trends in development of self-flowing mortar incorporating supplementary cementitious materials

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Abstract: Self-flowing mortar (SFM) is being popular in recent time. Its' easy-placement nature makes it suitable for narrow or congested reinforced places. To comply with modern-age needs, many supplementary cementitious materials (SCMs) are gaining importance nowadays. Using industrial and agricultural wastes as SCM, ensures proper management of many hazardous materials and saves cost as well. Incorporation of these two techniques can offer cost-effective and environment-friendly solutions to many construction problems. Many researchers studied the effect of different SCMs on mortar properties in recent years. The objective of this study is to summarize the findings of recent experiments. This will help the experts of this field to optimize their mix design easily, as well as, the researchers to find the research gap and determine the direction of their future studies.

Keywords: Self-flowing mortar (SFM); Supplementary cementitious material (SCM); Silica fume; Fly ash; Recycled glass powder.

1. Introduction

Self-flowing mortar (SFM) is a kind of fresh mortar mix, that can fill an enclosed area and consolidate under its' own weight, without any mechanical vibration. In narrow spaces or places with congested reinforcements, where placement and compaction are difficult, SFM can easily be used. This type of mortar requires less labour, time and power than the conventional ones. The absence of mechanical vibration also minimizes noise at the work site.

Production of cement requires a lot of fossil fuel, which generates a lot of greenhouse gas. Lowering the consumption of OPC will lower greenhouse gas emission. On the other hand, industries, like thermal power generation, steel production etc., produce tons of byproducts and wastes. Agricultural products, like rice, palm oil etc., also leaves behind huge wastes. It takes a huge effort and also cost to dispose of these materials. Unless proper disposal, these materials may cause serious environmental hazards. Some of these byproducts possess pozzolanic properties. If these wastes can be used as a partial substitution of OPC, it will save considerable cost to produce cement and generate less greenhouse gas. Additionally, it will ensure proper processing of these hazardous byproducts.

Supplementary cementitious materials (SCMs) are the materials which are used as partial replacement of ordinary Portland cement (OPC) to have desirable performance and save the cost of cement. Most of the SCMs are byproducts of industrial or agricultural processes. Some natural minerals can also be used as SCM.

An effective industrial use of SCMs, in the production of SFM, requires an optimization of different properties. The influences of different SCMs on the behavior of mortar are summarized in this article. This collective information will provide an overview about the trends of research and help the researchers of this field to find future direction.

2. Popular supplementary cementitious materials (SCM)

Most of the popular SCMs are agricultural or industrial wastes or byproducts, rich in Silica (SiO_2), Alumina (Al_2O_3) or Calcium oxide (CaO) content. Some of the natural minerals can also be used as SCMs. Figure 1 shows broad classification of popular SCMs.

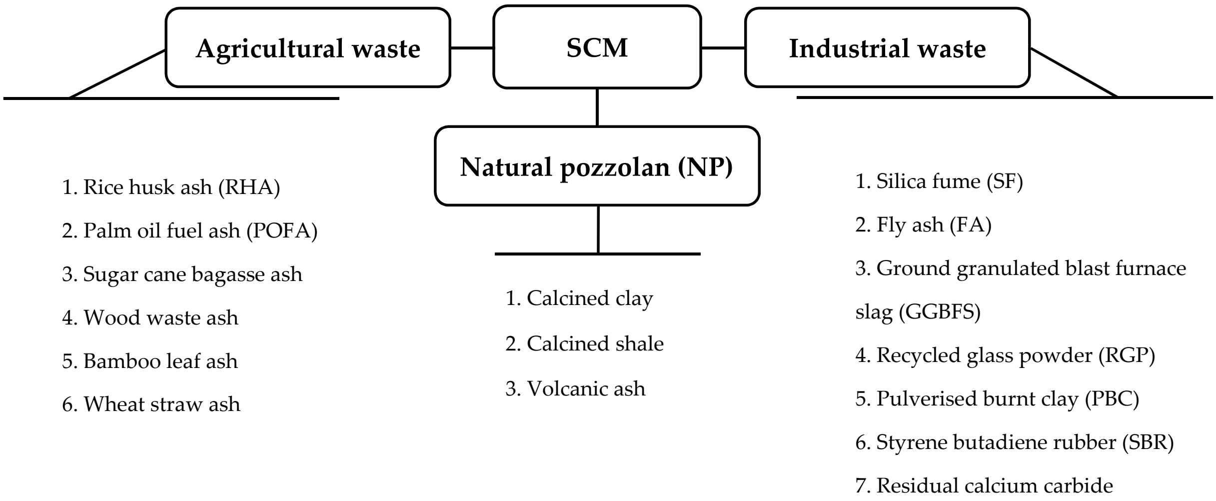

Figure 1. Classification of popular SCMs.

Chemical and physical properties of SCMs determine their influence on the mortar or concrete. Properties of recently used SCMs are summarized in Table 1.

3. Effects of SCMs

Both fresh and hardened properties of mortar are greatly influenced by the physical and chemical characteristics of SCM. Fresh properties indicate the flow and consolidation nature, whereas hardened properties indicate service strength and durability. Properties like density, porosity, water absorption, chloride permeability, acid resistance etc. provide indications about durability. Table 2. shows the tests conducted by the researchers in recent studies. In the later part, this article discusses the influence of popular SCMs on properties of mortar.

3.1. Flowability

Flowability is the property of fresh mix that determines the workability and compactibility. A mix with enough flowability may reduce the requirement of manpower and time for placement and eliminate the role of mechanical vibration. The particles of fly ash (FA) have relatively smoother surface and spherical shape compared to cement. Therefore, replacement of cement with FA lowers internal friction of the mortar mix and thus, increases its flowability. In an experiment conducted by Khotbehsara et al. (2015), the sample containing 30% FA showed more flow value with 42% less superplasticizer than the mix without FA [1]. A similar effect was observed in the study of Parghi & Alam (2016). Silica fume (SF) shows a consistent reduction in fluid nature of mix up to 25% replacement[2]. Palm oil fuel ash (POFA) has BET surface area of four times of OPC. Therefore, replacing OPC by POFA decreases workability of the mix. On the other hand, BET surface of pulverized burnt clay (PBC) is half of OPC. So, PBC shows an increase [3]. Burning POFA at a temperature of 600°C for 2 hours showed remarkable improvement. It increases SiO_2 content, reduces carbon and loss of ignition content and gives finer particles with 52% more surface area. Study showed a constant up trend in slump flow till 50% replacement of OPC by treated POFA and

Table 1. Chemical composition of SCMs.

Chemical composition (% mass)	NP	RGP	MK	GS	RHA	PBC	GGBFS	POFA	LP	FA	SF	OPC
	Senhadji et al. (2014)	Parghi & Alam (2016)	Yerramala et al. (2013)	Chindaprasirt & Rukzon (2014)		Hassan et al. (2014)	Memon et al. (2007)	Hassan et al. (2014), Alsubari et al. (2015)	Benabed et al. (2012), Senhadji et al. (2014)	Khotbehsara et al. (2015), Rao et al. (2015), Parghi & Alam (2016), Wongkeo et al. (2014)	Dawood & Ramli (2010), Parghi & Alam (2016), Wongkeo et al. (2014), Senhadji et al. (2014)	
Silica (SiO_2)	47.2	71.0	50.7	93.5	93.2	68.6	28.2	59.2 - 69.0	1.0 - 7.9	36.8 - 55.8	88.1 - 96.2	16.4 - 22.2
Calcium oxide (CaO)	10.8	8.5	0.4		1.1	0.3	50.4	5.0 - 6.0	45.5 - 52.6	2.6 - 18.6	0.0 - 1.5	49.9 - 68.3
Alumina (Al_2O_3)	18.9	8.0	45.8	5.0	0.4	20.6	10.0	3.7 - 3.9	0.2 - 2.6	20.0 - 24.7	0.6 - 5.4	4.2 - 6.7
Ferric oxide (Fe_2O_3)	10.0	0.9	0.4		0.1	4.7	1.8	4.3 - 6.3	0.2 - 1.1	5.4 - 30.1	0.2 - 2.0	2.5 - 6.2
Magnesium oxide (MgO)	4.4	0.4	0.1		0.1	0.3	4.6	4.1 - 5.2	1.7 - 2.1	1.0 - 2.2	0.6 - 1.5	0.7 - 4.5
Sulphur trioxide (SO_3)	0.5		0.0		0.9		2.2	0.4 - 1.6	0.1 - 1.0	0.4 - 2.8	0.1 - 1.0	0.6 - 4.4
Sodium oxide (Na_2O)	0.8	9.8	0.6		0.1	0.3	0.1	0.2 - 0.2	0.0 - 0.1	0.8 - 0.9	0.1 - 0.8	0.0 - 0.8
Potassium oxide (K_2O)	0.2	0.4	0.1		1.3	4.0	0.6	6.9 - 9.2	0.0 - 0.2	1.1 - 2.8	0.0 - 1.1	0.0 - 0.8
Titanium oxide (TiO_2)			1.3							0.5		0.0 - 0.2
P_2O_5								4.3		0.2	0.5	
Loss of ignition (%)	3.9	0.2	0.9		3.7			1.8 - 16.1	42.5 - 43.6	0.0 - 5.1	1.2 - 6.0	
Specific gravity (gm/cm^3)	2.6		2.5	2.6	2.2	2.7			2.7 - 2.7	2.1 - 2.3	2.2 - 2.4	

final slump flow was 730mm for concrete [4]. A similar improvement is expected for mortar. A rise in limestone content causes a fall in slump flow value. Having a higher specific surface area, limestone fines need more water than cement to wet the particles' surface [5]. Nano-CuO reduces free water in the mix while improving particle packing, resulting a reduction in the flow of fresh mix [1]. Nano-TiO_2 and nano-SiO_2 also showed the negative impact of fluid nature of mortar mix [6]. Smaller particle size than cement may also be a reason behind this phenomenon.

Table 2. Summary of tests conducted.

	Alsubari et al. (2015)	Benabed et al. (2012)	Chindaprasirt & Rukzon (2014)	Dawood & Ramli (2010)	Hassan et al. (2014)	Khotbehsara et al. (2015)	Memon et al. (2007)	Parghi & Alam (2016)	Rao et al. (2015)	Senhadji et al. (2014)	Wongkeo et al. (2014)	Yerramala et al. (2013)	Yerramala et al. (2014)
Slump Flow	X	X			X	X			X				
Spread Time	X												
V-Funnel	X	X				X			X				
J-Ring	X												
L-Box	X												
GTM screen stability	X												
rotational viscometer		X											
Density				X			X	X			X		
Compressive strength	X	X	X	X		X	X	X	X	X	X		
Flexural strength				X				X	X			X	
Impact strength													X
Toughness indices				X									
Water absorption						X	X	X	X		X		
Porosity										X	X		
Electrical resistivity						X							
Drying Shrinkage Strain	X												
Acid Attack (HCl)	X												
Acid Attack (HNO_3)										X			
Acid Attack (H_2SO_4)										X			
loride penetration test (RCPT)			X			X							
Electrical Indication of Resistance of Chloride Ion Penetration											X		
Chloride immersion test (CIT)			X										
Carbonation resistance									X				

3.2. Strength

Strength is the most important property of cement based materials. SF reduces the porosity and creates bonds between particles by pozzolanic reaction with $Ca(OH)_2$, thus improves the strength properties. In the concrete mix, 5-10% SF improved compressive strength over the control mix [7]. Same analogy was also applied on mortar mixes. 15% SF enhanced compressive strength of mortar by 17% and reached to 63.8MPa in 28 days at 0.4 w/c ratio [8]. Senhadji et al. also observed similar fact [9]. Though strength gain rate was a little slow at early age, the addition of 5%, 7.5% and 10% of SF caused an increase in strength by 5%, 6% and 10% respectively at 360 days [9]. High silica and aluminium dissolution by recycled glass powder (RGP) lead to a good pozzolanic reaction. Compressive and flexural strength increased considerably by RGP addition. 25% RGP achieved 35MPa and 55MPa compressive strength in 28 and 90 days respectively, which was 29.6% and 41% higher than the control mix. SF, FA & styrene butadiene rubber (SBR) were used with RGP in different combinations and showed significant improvement in strength properties. A blend of 25% RGP and 10% of FA, SF and SBR each, boosted up the 28 days' compressive strength by 144%

compared to the OPC control mix. This blend achieved 66MPa and 85MPa in 28 and 90 days respectively. Flexural strength also showed similar improvement [2]. Due to the slow pozzolanic reaction and the dilution effect, FA has an adverse effect on strength. Wongkeo et al. (2014) tested 50-70% FA in the concrete mix. In every mix, strength dropped as the FA content raised. In a combination with SF, FA showed better performance [7]. A similar trend was observed in tests on the mortar. Compressive strength went down for a 20% to 30% replacement by FA [1]. Ground granulated blast furnace slag (GGBFS) has a positive influence on mortar strength. 50% replacement of OPC resulted in 5% to 15% more compressive strength, which was more prominent at lower binder ratio [10]. In one study limestone fine (LF) improved mortar strength up to 10% replacement [5]. Another study had a contradictory outcome, where, compressive strength went down with increasing LF ratio at all ages. 10% substitution caused 5.9% drop in strength [9]. Flexural and impact strength of mortar rises with a rise in Metakaolin (MK) content up to 15%. 10% replacement maximizes the enhancement, which is about 34% [11,12]. Natural pozzolan (NP) induced reductions of 90 days' compressive strength by 9, 11 and 17% for 15, 20 and 25% replacement, respectively. The slow pozzolanic reaction between the glassy particles of NP and the C–H is the cause of this reduction [9]. Micro-filler effect of the burnt POFA improves the overall strength, especially early-age strength of the concrete. On the other hand, the SiO_2 of the treated POFA reacts with $Ca(OH)_2$ to form a secondary calcium-silicate-hydrate (C-S-H), which makes denser concrete. 10-50% substitution of OPC by burnt POFA made stronger concrete. 20% replacement made a rise over 20% in 56 days [4]. The similar positive effect is expected in the case of mortar. 20% Rice husk ash (RHA) gave the strength of 102% to 104% of OPC mortars. In case of 40% replacement, it is 77-103%. Up to 40% replacement by a blend of equal amount RHA and ground river sand (GS) achieved at least 77% strength of OPC mortar. The performance of the blend of RHA and GS was probably caused by synergic effect between a fine pozzolan and a fine inert material. According to ASTM C618, pozzolan mortar should have a strength activity index of at least 75 % of the control mortar [13].

3.3. Chloride penetration

Chloride ions' penetration in the concrete causes corrosion of embedded steel. Chloride transportation occurs through hardened mortar by absorption and diffusion. FA and nano-CuO reduce chloride permeability. In a study, permeability was reduced by about 25% by 20-30% FA. Adding 1-4% nano-CuO in the presence of FA caused further reduction. The sample with 25% FA and 4% nano-CuO had a drop of about 62% [1]. Chloride resistance of concrete, containing FA or SF increased with increasing FA and SF content, which is more prominent in lower w/b ratio. 49.4% and 92.2 % increment was recorded by 70% FA and 10% SF respectively. Mixtures of FA & SF also made remarkable development [7]. Use of GRS as cement replacement made the mortar more vulnerable against chloride attack. 20% GRS caused 53% reduction of resistance in 28 days. Chloride resistance of mortar increased with the increasing ratio of RHA. The inclusion of 40% RHA made a fall of rapid chloride penetration test (RCPT) result from 7500 Coulombs for OPC to only 200 Coulombs. Equal mixtures of RHA and GS gave satisfactory results [13].

3.4. Density

In the experiment of Wongkeo et al. (2014), use of SF & FA in binary and ternary blends showed no significant difference or a general trend in the density of concrete [7]. In another study Parghi & Alam (2016) found a little higher density using 10% FA. In different combinations of RGP, FA, SF & SBR significant amount rise in density was observed. Replacement of 25% OPC by RGP produced mortar of 2345 kg/m^3 density which was 3.5% more than the control specimen. A combination of 45% OPC, 25% RGP and 10% of each FA, SF & SBR gave a rise in density of 6.64% and a final value of 2410 kg/m^3 [2]. GGBFS did not show any remarkable change at lower binder ratio. At binder ratio 1:2, 60% GGBFS caused 3% less density [10].

3.5. Porosity

Porosity is the property which is influenced by all the parameters related to mix ratios. It acts as a detailed record of these influences. Inclusion of 20% NP, 7.5% SF and 10% LF reduced porosity by 47%, 14% and 18% respectively [9]. They also reported a decrease in mean pore size by 73%, 40% and 48% [9].

3.6. Water absorption

Water absorption depends on porosity. Up to 25% FA incorporation decreased the water absorption, though 30% FA caused about 3% increase than that of the control sample. It was seen that the water absorption of specimens reduced with the increase of nano-CuO particles from 1% to 4% [1]. Nano-SiO_2 and nano-TiO_2 remarkably boosted water absorption [6]. Incorporation of various combinations of RGP, FA, SF & SBR reduced water absorption of mortar. 25% RGP caused 31.58% drop in water absorption [2]. Replacing OPC by 25% RGP and 10% of each FA, SF & SBR gave a drop in water absorption of 52.63% and kept below 3%. Formation of better bond among the polymer cement modifier, SCMs and cement matrix caused higher water resistance capacity [2].

3.7. Acid resistance

As the durability of mortar is as important as the strength, the resistance of SCM mortars in aggressive media such as sulphuric and nitric acids should be studied. Mortars containing 5%, 7.5% and 10% SF suffered 25%, 23% and 30% fewer losses in weight than OPC mortar by an exposure to 5% HNO_3 for 56 days [9]. Use of NP and LS also enhanced resistance by about 17%. A different trend was observed in a similar test with 5% H_2SO_4. SF containing specimens suffered more loss than OPC, though NP and LF performed well. 15% LF induced 33% more resistance against H_2SO_4 [9]. Mixing POFA resulted in better sustainability against 3% HCl. Burnt POFA was a little better than ground POFA. After 1800 hours' exposer, 10% treated POFA saved about 25% loss; while 50% treated POFA had a mass loss less than 2% [4].

4. Conclusions

Constituent materials of a mortar mix control its' flowability, strength and durability to a great extent. For an effective industrial application, mix design should be prepared for a good strength, flowability and durability, using locally abundant and cheap supplementary cementitious materials (SCMs). This article gives an overview about how the properties of mortar are influenced by some popular SCMs. This overview will help the professionals to choose an SCM to serve their purpose and the researchers to look deeper into some promising materials and to find new materials as well.

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Conflicts of Interest: The authors declare that, there is no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SFM: Self-flowing mortar
SCM: Supplementary cementitious material
OPC: Ordinary Portland cement
SF: Silica fume
FA: Fly ash

POFA: Palm oil fuel ash
GGBFS: Ground granulated blast furnace slag
MK: Metakaolin
RGP: Recycled glass powder
PBC: Pulverised burnt clay
SBR: Styrene butadiene rubber
RHA: Rice husk ash
LF: limestone fine
NP: Natural pozzolan
GS: ground river sand

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