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AN OVERVIEW OF THE EFFECT OF FLY ASH AND SILICA FUME ON THE CEMENT HEAT OF HYDRATION

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Abstract: Over years, the incorporation of pozzolanic supplementary cementitious materials (PSCM) in concrete have been increasing tremendously. Two of the most notable PSCM are fly ash (FA) and silica fume (SF), which have been proven to enhance some of the properties of concrete. Previous research shows that the use of PSCM in concrete serves many purposes. Several studies focused on the assessment of the ability of PSCM to reduce the heat released during the hydration process of cement when incorporated in the concrete mix. It is very desirable to minimize the cement HH especially in mass concreting as it may induce thermal stresses that may lead to the failure of the structure. This study focuses on the performance of FA and SF with respect to their effect on the cement heat of hydration (HH) as reported in the literature. The paper summarizes the most important findings of previous studies conducted on the effect of FA and SF on the HH, and shed the light on the conformity and discrepancies between different studies results. The paper should prove useful for future researchers and practitioners interested in studying the effect of FA and SF on the HH of cement.

1 INTRODUCTION

The hydration of cement is an exothermic reaction that can release a tremendous amount of heat. This heat of hydration (HH) can cause a rise in the concrete temperature. Due to environmental effects, the exterior of concrete tends to cool at a faster rate than its interior; this creates a temperature gradient between the inner and out concrete. As such, the rates of expansion and contraction of the concrete core and its surface differ due to this temperature gradient, which can create thermal stresses. If the thermal stresses developed exceeds the tensile strength of concrete, thermal cracks start to occur. Thermal cracks usually occur in random pattern on the surface of concrete; they occur few days after stripping the forms perpendicular to the longest axis of the concrete member (NRMCA 2009). This phenomenon becomes very critical in mass concrete members due to the huge amount of HH released and the substantial difference in temperature between the core and the surface of the mass concrete member. As such, it is recommended that the temperature difference between the different layers of the concrete member should not exceed 20°C (Portland Cement Assoc. 1997).

Mass concrete members are recognized by their large dimensions. The American Concrete Institute (ACI) considers any concrete member that has a minimum dimension of 4 feet (1.3m) as a mass concrete member (ACI 2007). Other factors of considerations that would classify the structural element as a mass concrete member is the volume to surface ratio, and the inclusion of high heat-generating admixtures in the concrete mix (NRMCA 2009). Examples of mass concrete structures are mat foundations, dams, and thick walls. Special precautions should be taken to control the HH when dealing with mass concrete structure.

There are several methods that can be used to control the heat gradient in mass concrete structures. Controlling the HH can be achieved by altering the concrete mix design by using low-heat cement or incorporating PSCM that are known to reduce the HH, such as slag and FA (Briley 2004, NRMCA 2009, Patil 2015). Also, the precooling of concrete aggregates contributes significantly to reducing the peak temperature of the concrete mix after placement. Several construction methods are known to be efficient in reducing the HH; one of them is post cooling of concrete using cooling pipes (Zhu 1999, Kim et al. 2001, yang et al. 2012). Proper insulation of the concrete members and pouring concrete in thin lifts can reduce the heat gradient significantly (Gajda and John 2016). This study focuses on the effect of two types of PCSM on the cement HH, which are FA and SF. The study presents the results documented in the literature about the effect of FA and SF on the cement HH, and highlights the consistency and discrepancies of the results reported.

2 PROBLEM STATEMENT AND OBJECTIVE

The effects of FA and SA on different properties on concrete have been investigated in a multitude of studies. A particular interest was given to the effect of those materials on the HH of cement. There are several studies that focused on this aspect. However, there is not a single a study that presents a thorough review of the work that has been done before. This paper aims to provide an organized and categorized concise review and analysis of findings of previous studies from the literature that addressed the effect of FA and SF on the cement HH.

3 METHODOLOGY

The methodology adopted on this research focused on reviewing the studies investigated the effect of FA and SF on the HH of cement. The literature included all the literature between 1980 and 2016. The identified studies were grouped and categorized by material type, as shown in Figure 1. The main points of each study were summarized with a main emphasis on the findings. The discrepancy between the results obtained from different studies were highlighted to identify existent gaps and inconclusive findings in the literature.

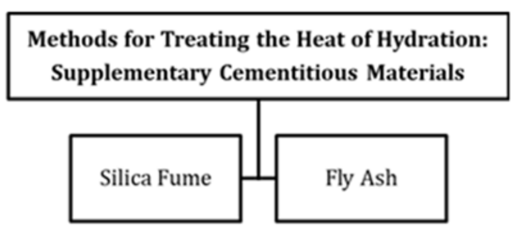

Figure 1: Categorization of previous studies focused on the utilization of supplementary materials to treat the HH

4 SUPPLEMENTARY MATERIALS USED FOR REDUCING THE HEAT OF HYDRATION

The effects of many PSCMs on the HH of cement have been considered on a multitude of studies. However, the majority of research focused primarily on FA and secondarily on SF. The following section will discuss the details of these studies and the most important findings reported.

4.1 Fly Ash

Fly ash is a common PSCM that was investigated in many papers for its effect on the HH of cement. A conduction calorimeter was used to test FA as a 10% and 20% replacement of PC. Also, the study investigated the effect of FA when mixed with a plasticizer. The results showed that FA was able to reduce HH; as the quantity of FA increased the HH decreased. The tests done on the mixes with the plasticizers showed that there was more heat release compared to the samples made with FA and PC only; however, it was still less than the HH of the control sample (Meland 1983).

Three different types of Turkish fly ash were tested using standard ASTM C186 in percent replacements of PC of 10%, 20%, and 40% (Tokyay 1988). One of the fly ashes was a high-calcium, while the other two were low-calcium. The results showed that the low-calcium fly ashes were more effective in decreasing the HH when compared to the high-calcium FA. Of all mixes that contained the three FAs used at different percentages, the mix that had a higher HH than the control mix was the one that contained the high-calcium FA at a 10% replacement. This occurred due to the high heat evolving lime and anhydrite in the high-calcium FA (Tokyay 1988).

Different mixtures were tested with FA replacing cement to up to 70% fly ash (De Rojas et al. 1993). The four mixtures that were tested contained 50%, 60%, and 70% FA replacements of PC in addition to a control mix made with 100% PC for comparison purposes. The results show as the percentage of FA increases in the mix, the peak temperature decreases, as shown in Figure 2 (De Rojas et al. 1993).

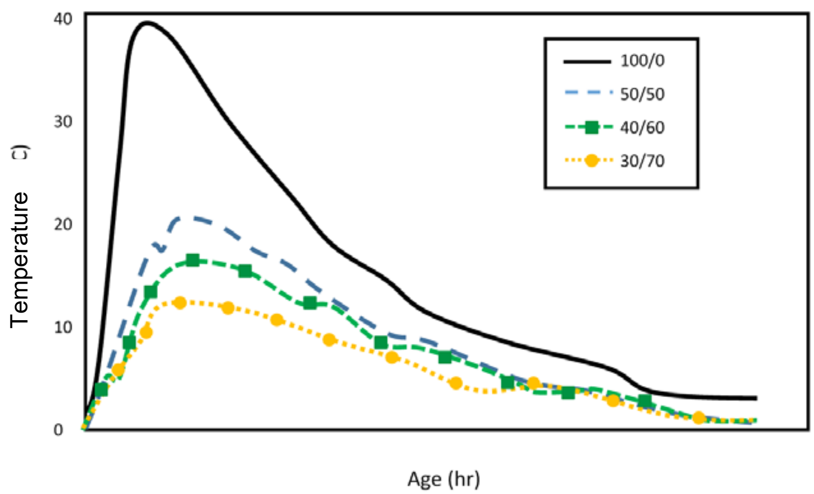

Figure 2: The heat of mixes at different fly ash percentages (De Rojas et al. 1993)

The testing of the effect of FA on the HH was done in different room temperatures using mixtures of 70% PC and 30% FA (Alshamshi 1994). The room temperatures used in the study were 20°C, 35°C, and 45°C. The peak temperatures of the mixes were compared to each other. The results showed that the increase of the room temperature caused the heat peak to increase. While the HH did not decrease in hotter temperatures, it was still concluded that using FA as a partial replacement could provide an advantage in reducing the effects caused by the HH such as thermal cracking (Alshamshi 1994).

A semi-adiabatic calorimeter was used to compare the results of a FA mix to another made with SF (De Rojas and Frias 1995). The mixtures were done with 30% replacement of PC each and the results, see Figure 3, shows that FA can decrease the HH. This is due to the fact that FA has a slower pozzolanic activity compared to SF (De Rojas and Frias 1995).

In another study, FA was used as a replacement of 10% and 30% of PC pastes and mortars (Frias et al. 2002). The findings of this study verified that the increase in the amount of FA used in the mix has a significant effect on decreasing the HH. The tests on the mortars further also showed a significant reduction in the HH with a difference of up to 80 J/g of the HH of the control mix (Frias et al. 2002).

Atis (2002) used an adiabatic system to test the HH associated with using high volumes of FA in the amount of 50% and 70% replacements of PC. Separate samples that contained plasticizer were tested along with a mix of 100% PC to be used as the control. The results showed that the samples that contained FA had lower peak temperature compared to the control mix; the addition of the plasticizer increased the peak temperature. The study concluded that as the quantity of the FA increased, the peak temperature decreased (Atis, 2002).

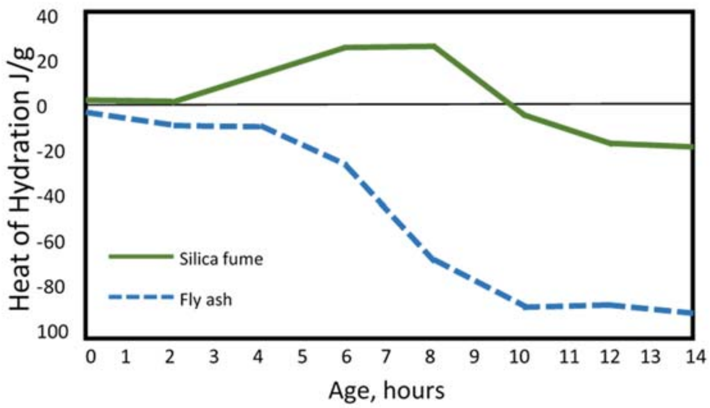

Figure 3: Comparison of the HH between SF and FA (De Rojas and Frias 1995)

An isothermal calorimeter was used to test class C fly ash with different w/c ratios (Langan et al. 2002). The samples contained w/c ratios of 0.35, 0.40, and 0.50 with replacement of 20% of PC using FA and were tested for 72 hours. The results found in this paper showed that higher w/c ratios delay the peak temperature. The heat evolution after one day was lowered as the w/c ratio increased. FA and SF were also mixed together in a sample that contained 20% FA, 10% SF, and 70% cement. This mixture was able to reduce the heat slightly and delay the peak temperature. (Langan et al. 2002).

Class C and Class F FA were both tested and compared to each other in mixtures that contained replacements of 15%, 25%, and 35% of PC (Schindler and Folliard 2003). Both Class C and Class F fly ashes with the highest replacement amount (35%) had the lowest adiabatic temperature rise when compared to the control sample (100% cement). However, after 40-50 hours, the heat release of the samples made with Class C FA showed an increase exceeding the HH released by the control sample. It was concluded that Class F FA is a better option for reducing the HH than FA Class C.

A separate study tested Class F FA at different w/b ratios as a replacement of 25%of PC (Pane and Hansen 2005). The test from the w/b ratios of 0.35 and 0.45 showed that decreasing the w/b ratio lowers the heat released (Pane and Hansen 2005).

More FA tests were conducted as well as a combination of FA with metakaolin (Snelson et al. 2008). The experiments on FA consisted of 10%, 20%, 30%, and 40% replacements of PC. The results confirmed previous findings with respect to decreasing the HH by increasing the percentage of FA added. The addition of metakaolin to the mixture proved to not be as effective as fly ash alone. A mixture of 15% metakaolin and 5% fly ash caused the HH to be greater than the control sample due to the large amount of metakaolin added (Snelson et al. 2008).

Additional studies were conducted on samples that contained 20%, 40%, and 60% FA as a replacement of PC (Maia et al. 2011). The results -see Figure 4- shows that increasing the amount of FA in the mix leads to a significant decrease in the HH released (Maia et al. 2011).

Different fly ash and slag combinations were tested using adiabatic calorimeter to ass their effect on the HH (Lee et al. 2014). The two samples tested included a mix of 30% cement, 50% slag, and 20% fly ash and another one of 40% cement, 40% slag, and 20% fly ash. In both mixtures, the fly ash content stayed the same, but the tests showed a reduction in the peak temperature of both mixes. The peak temperature of the control mix was 37.5°C while the 50% slag mix had a peak of 24.5°C and the 40% slag one peaked at 30°C. There was no information provided in the study regarding the cause of the decrease in the peak temperature and it was not stated if it was due to the decrease in cement or effect of slag (Lee et al. 2014).

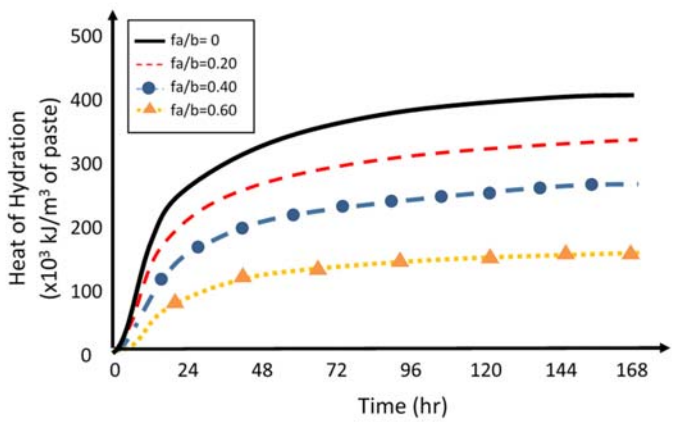

Figure 4: The heat of hydration at different fly ash ratios with w/b=0.45 (Maia et al. 2011)

The most recent study on FA used it as replacement of 25% of PC in comparison to a 100% PC control sample (Alhozaimy et al. 2015). The results from that test showed that the HH for the control sample was 252.76 J/g, while the FA sample had a HH of 206.97 J/g. A total decrease of 19.1% in the HH was observed when the samples were compared (Alhozaimy et al. 2015).

4.2 Silica Fume

The impact of SF on the HH of concrete have been discussed in multiple studies. An early study from 1983 documented different tests conducted of SF blended together with slag to reduce the heat released from the hydration of cement (Lessard et al. 1983). The mixture used in the study consisted of one mixture made with 35% slag and 15% condensed silica fume as a replacement of Portland Cement (PC). When it was compared to the control sample that is made of 100% PC, it was found that mixture of SF and slag led to a substantial reduction in the heat released. However, the study did not specify whether this decrease was due to the effect of slag, silica fume, or the lower cement content. The results from the study also showed a reduction of 30% and 22% of the HH, when isothermal temperature of 20°C and 40°C were used respectively (Lessard et al. 1983).

Another study by Meland (1983) provided more results on the performance of SF replacement of PC with respect to the HH released. Samples made with SF as 10% and 20% replacement of PC as well as another sample composed of PC, SF and lignosulphonate (plasticizer) were prepared and tested in a conduction calorimeter. The results show that the HH decreased slightly with the addition of S. It was noticed that by increasing the percentage of PC replacement with SF, the HH continued to decrease. On the other hand, when the lignosulphonate was incorporated in the mix with the silica fume, a larger amount of the HH was released compared to the control mix. This increase in the heat was explained by the possible absorption of the lignosulphonate by SF, which increased the amount of heat released (Meland 1983).

Cheng-yi and Feldman (1985) presented a study to test samples made with SF replacements of PC of 10%, 20%, and 30% using a conduction calorimeter. After testing the samples for 72 hours, the results showed that increasing the amount of SF in the mix yields a greater heat release. This was attributed to the early pozzolanic reaction of SF or the acceleration of cement hydration (Cheng-yi and Feldman 1985).

The Langavant Calorimeter method, a semi-adiabatic method, was used to test SF at 20°C (De Rojas and Frias 1995). Percentage replacements of PC were done using 5%, 10%, 15%, and 30% of SF. Also, samples containing 6 different types of SF were also tested at 10% replacements of PC. The results showed an increase in the HH when the SF was used in relatively small quantities of 5%, 10%, and 15% as a replacement of cement compared to control samples made with plain cement. However, when the quantity of SF was increased to a replacement of 30% of PC, the results showed a small decrease in HH. It was then concluded that the pozzolanic activity in the silica fume caused the increase in heat. However, the large replacement of PC in the 30% samples decreased the HH released from the PC hydration, which counteracted the heat released due to the pozzolanic reaction of SF. The tests conducted on the different samples representing the 6 types of SF showed an increase in the heat released compared to the control samples. Some of the experiments results are shown Figure 5 (De Rojas and Frias 1995).

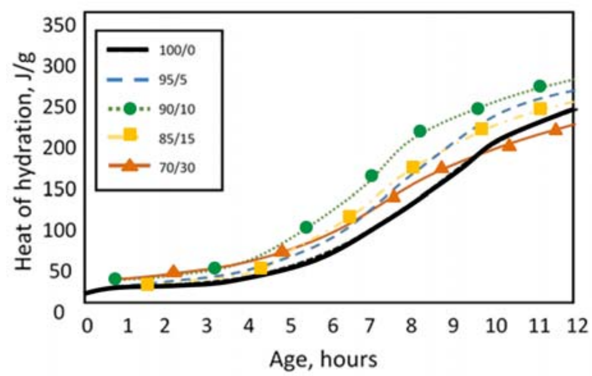

Figure 5: HH at different SF percentages (De Rojas and Frias 1995)

De Rojas and Frias (1996) continued their previous work where they further proved that only a large amount of SF could slightly decrease the HH. It was explained that this due to the great reduction in the amount cement and consequently a reduction in the HH associated with the cement hydration. However, SF still undergoes a pozzolanic reaction, which contributes to the heat release but at a lower rate (De Rojas and Frias 1996).

Semi-adiabatic experiments were done for 22 hours on sample made with 10% SF replacement of PC using different water-cement (w/c) ratios (Persson 1997). The results show that as the w/c ratio increased, the HH increased as well. Additional tests with silica fume and superplasticizers were done and the results showed that the mixture with 10% silica fume, 1.63% superplasticizer, and a w/c ratio of 0.24 had the lowest heat release (Persson 1997).

Mortar mixtures that contained SF were tested in another study in PC replacements of 10% and 30%. The results found were similar to ones in previous studies where the 10% mixture released a higher amount of heat compared to the control samples. However, the 30% samples released less heat compared to the control samples (Frias et al. 2000).

In another study, samples made with 10% SF replacements of PC were tested with different w/c ratios of 0.35, 0.40, and 0.50 (Langan et al. 2002). An isothermal calorimeter was used at 25°C to test the samples. It was found that samples contained SF released higher amount of heat compared to the control samples. As for the samples made with the different w/c ratios, the conclusion was that the increase in the w/c ratio caused the SF samples to liberate the HH at a higher rate compared to the control sample (Langan et al. 2002).

More tests using different water to binder (w/b) ratios were done using an isothermal calorimeter (Pane and Hansen 2005). The tests performed consisted of a 10% SF replacement of PC with w/b ratios of 0.45 and 0.35. The results showed that the SF samples released a low amount of heat at the beginning, but it quickly increased. The mixture made with a w/b ratio of 0.35 released less heat than the 0.45 mixture, but both mixtures still produced more heat than the 100% cement sample (Pane and Hansen 2005).

Silica fume mixtures were tested at percentages of 10%, 20% and 30% PC replacements (Mostafa and Brown 2005). Similar to previous results, low heat release was detected at the beginning of the tests, but after 25 hours, the mixture made with 10% SF replacement had a higher HH than the rest of the samples. It further proved that the decrease in HH for the samples made with larger quantities of SF is related to the reduction in the amount of PC in the mix rather than the effect of SF (Mostafa and Brown 2005).

A different study used semi-adiabatic calorimetry for 10 days to test 16 different samples (Kadri and Duval 2009). The samples had different percentages of SF replacements of PC of 0%, 10%, 20%, 30%, and 40% as well as different w/b ratios of 0.25, 0.30, 0.35, and 0.45. The results of some of the tests discussed in this study is shown in Figure 6. The graphs show that during the first 24 hours, the HH of the SF samples is greater than the HH of the control mix. The findings of this study also show that as the w/b ratio increases, the heat released increases (Kadri and Duval 2009).

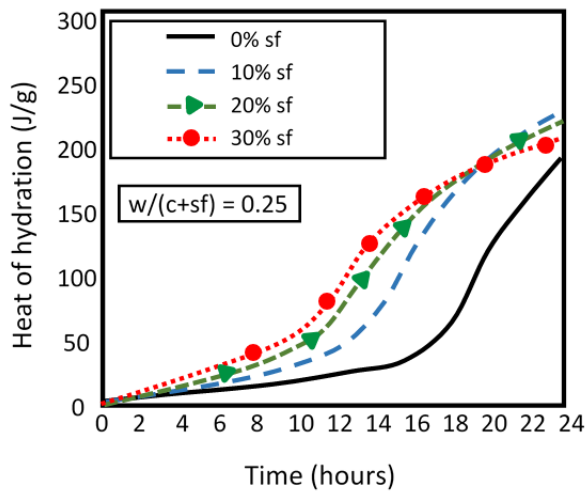

Figure 6: Heat of hydration of different SF percentages at two w/b ratios (Kadri and Duval 2009)

Additional tests were done using samples that contained SF in the percentages of 5%, 10%, and 15% as PC replacement to compare the amount of HH released (Maia et al. 2011). The results provided in this study were different than the ones in different papers. In this study, it was reported that SF decreased the HH slightly compared to a control mixture, as shown in Figure 7. The results show that as the percentage of SF increases, the HH released decreases (Maia et al. 2011). The findings of this study show discrepancy in the results compared to other studies.

Kadri et al. (2011) conducted a test using only one sample that contained SF as a 10% replacement of PC. It was compared to a control mix that contained 100% PC. The results concurred what was stated in previous studies; the addition of SF increases the HH (Kadri et al. 2011).

A recent study provided results for experiments that were conducted for 72 hours on mixtures that contained ground SF as a 25% replacement of PC (Alhozaimy et al. 2015). The results for the SF mixture showed that there was 15% reduction in the HH when compared to a control sample. The results from the concrete samples that contained ground SF also showed that the total HH was reduced along with its peak heat. The results obtained using ground silica fume are different from the results of the SF samples. This difference in behavior was attributed to the to the high crystallinity of the ground silica fume, which diminishes its chemical reactivity.

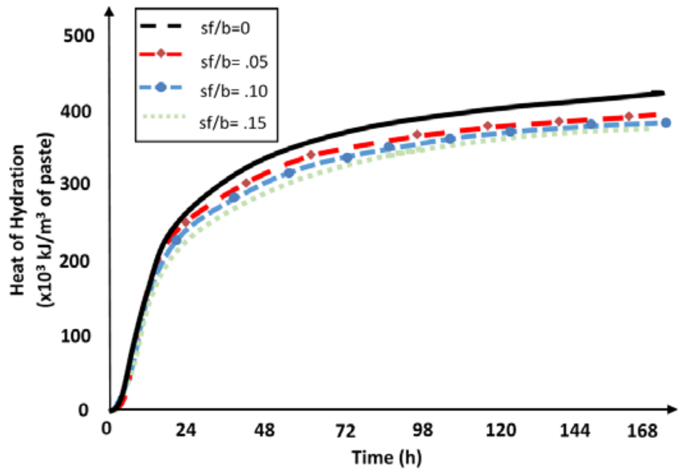

Figure 7: Influence of SF content on the HH (Maia et al. 2011)

5 FINDINGS

This paper presents a review of 14 previous studies that were conducted to assess the effect of FA the HH of a cement mix. The results reported in these studies seem to be consistent regarding the ability of FA to reduce the HH. The observed behavior was that increasing the amount of FA in the mix leads to a greater decrease in the amount of heat released and the peak temperature. However, special attention should be given to the calcium and anhydrite contents in the type of FA used as higher contents of calcium and anhydrite may increase the HH released (Tokyay 1988, Schindler and Folliard 2003). When FA was combined with other PSCMs and admixtures, the results were contradictory. The results show that FA is compatible with slag as they positively reinforce the tendency to lower the HH in a cement mix when combined together. On the other hand, Metakaolin and plasticizers seem to counteract the capability of FA to lower the HH of the mix. The most important results of previous studies conducted on the effect of FF on the HH is given in Table 1.

Table 1: Summary of the most important findings about the effect of FA on the HH

Material	Replacement (%)	HH (J/g)	Reference
Fly Ash (unclassified)	10%	185	(Meland, 1983)
		250	(Snelson et al., 2008)
		260	(Frias et al., 2000)
	20%	170	(Meland, 1983)
		235	(Snelson et al., 2008)
		275	(Maia et al., 2011)
	25%	206	(Alhozaimy et al. 2015)
		220	(Pane and Hansen, 2005)
		250	(Pane and Hansen, 2005)
		215	(Pane and Hansen, 2005)
		225	(Pane and Hansen, 2005)
	30%	275	(De Rojas et al., 1993)
		330	(Cheng-yi and Feldman, 1985)
		200	(Frias et al., 2000)
		200	(Snelson et al., 2008)
		275	(De Rojas et al., 1996)
	40%	285	(Snelson et al., 2008)
		205	(Maia et al., 2011)
	60%	120	(Maia et al., 2011)

The results of the SF as reported in the literature are quite contradictory and inconclusive. Most studies showed that the addition of SF leads to an increase in the HH of the mix. However, increasing the amount of SF beyond a certain limit leads to a decrease in the heat released. The explanation of this observation is quite inconclusive as it is not clear whether the reduction of the amount of PC used is the main factor for the decrease in the HH or not. The threshold for the percentage of SF replacement needed to start noticing a decrease in the HH is undetermined. A study reported contradictory results regarding the effect of SF on the HH of a cement mix. The study indicates that increasing the percentage of SF replacements of PC will lead to a decrease in the HH generated (Maia et al. 2011).

6 CONCLUSIONS

This paper presents a comprehensive review for 28 studies conducted on the effect of FA and SF on the HH of a cement mix. For the most part, the results on the behavior of FA are conclusive and consistent. The addition of FA leads to a decrease in the HH of the mix. However, careful consideration should be given the calcium and anhydrite contents in FA, as they may lead to different results. The majority of studies conducted on SF reported an inefficient behavior regarding the ability of SF to lower the HH of a cement mix. However, the results are contradictory given the fact that a recent study reported opposite results. As such, new methods are needed to study the behavior of PSCM with respect to their effect on the HH. Also, further classification of SF types needs to be established based on the chemical composition of the type used.

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