Early Age Strength and Heat of Hydration Properties of Concrete containing Silica Fume and Metakaolin

Khawaja Adeel Tariq*, Sajid Mehmood, Muhamamd Haroon, Ahmad Raza

Department of Civil Engineering, Chenab College of Engineering and Technology Gujranwala, Pakistan

* **Correspondence Author:** Email: khawajaadeel@hotmail.com

Abstract

This research work is related to heat of hydration and mechanical properties of the concrete containing silica fume and metakaolin. Total five mixes of concrete were prepared with varying percentages of metakaolin and silica fume. The heat of hydration, tensile strength, compressive strength and flexural strength of concrete that contain silica fume and metakaolin were determined by testing cylinders, beams and cubes. There was replacement of silica fume and metakaolin as 10% and 0-15% respectively in all mixes except control mix. The rise of temperature due to heat of hydration in concrete was calculated by using semi adiabatic approach. The strength of concrete with silica fume and metakaolin increases with curing age as compared to control mix. It was observed that when quantity of metakaolin is increased from 0-10% in silica fume concrete, the temperature rise of concrete was reduced. It was also perceived that further increase in metakaolin i.e. 15% in silica fume concrete results in reduction of strength. Therefore, it can be inferred for the study that silica fume concrete with metakaolin can be used in colder areas where early age strength is required and in mass concrete construction where lower temperature is needed.

Key Words: Concrete, Heat of Hydration, Silica Fume, Metakaolin

1. Introduction

The engineering material that is mostly used in the construction of dams, buildings, bridges and industrial structures is concrete. Quality of concrete is improving day by day to attain lower prices, better characteristics and to make it compatible with the environment [1]. It has been well recognized that the cement supplementary material i.e. silica fume (SF) and metakaolin (MK) are pozzolanic materials which have no direct cementitious value, but in the presence of moisture it reacts chemically with calcium hydroxide to formulate compounds which possess the cementitious capabilities [2]. The MK is comparable to SF in pozzolanic reactivity [3] and in recent times, there has been an interest developed to utilize MK as a mineral admixture for cementing materials. The use of MK also reduces autogenous shrinkage at early ages [4]. MK is an alumina-silicate material that is thermally activated and is obtained within the temperature range 650-800°C by purification of kaolin clay. It had been observed that the concrete which consists of 10% MK replacement possess the high compressive strength as compared to the conventional concrete in later ages [5]. The shrinkage and drying properties of MK concrete is less than that of plain concrete but same to that of SF mixtures [3]. The same quantity of MK and SF in plain concrete depicted that MK gives good strength outcomes at early days but in the longer run the strength outcomes of SF and MK are marginally the same. Moreover, with respect to durability properties by penetration point of view, the MK concrete provided more resistance than normal concrete [6].

The optimum replacement level of MK with cement is reported as 15% [7]. The later ages strength of concrete is not negatively affected by the use of MK while the early age strength significantly rises [8]. The use of SF in concrete, increases early days strength of concrete but it also increases the hydration rate of cement concrete. This results in increasing of thermal stress in concrete and formation of thermal cracks [9]. In past mostly researchers have worked separately on SF and MK concrete and have investigated mechanical and Hear of Hydration (HOH) properties. However, experimental data is very scarce with combined effect of SF and MK on concrete at early day's strength and its HOH properties. Thus, the current research work is associated with the heat of hydration (HOH) properties and mechanical properties of concrete with varying contents of SF and MK.

2. Experimental Program

2.1 Materials

Ordinary Portland cement (OPC), SF (Fig. 1), MK (Fig. 2), crush aggregate and sand were used to make the test specimens. SF and MK were purchased locally. Uniformly graded sand was used that had passed through a 4.75mm sieve. The crushed aggregate average size was 16-20mm. The particle densities of SF, sand, MK and cement were 0.3, 1.58, 1.005, 3.15 g/cm^3 respectively. The composition of SF; and OPC and MK is given in Table 1 and Table 2 respectively.

Table 1: Composition of SF

Type	MS-85 [10]
Silicon dioxide	More than 85%
Colour	Black/dark gery
Moisture content	Less than 3.0%
Loss of ignition	Less than 6.0%
Quantity per 100 binder	5 to 15 kg
Retained on 45µm sieve	Less than 10%
Specific surface area	More than 15 m^2/g
Dry Bulk density	600-750kg/m^3
Flash point	No

Table 2: Composition of OPC and MK

Compound	Material	
	OPC	**Metakolin**
Al_2O_3	5.50	59.90
SiO_2	22.0	32.29
CaO	64.25	0.04
Fe_2O_3	3.50	1.28
MgO	2.50	0.17
K_2O	1.0	2.83
Na_2O	0.20	0.24
LOI	0.64	2.80

Fig. 1: Silica Fume (SF)

2.2 Materials

For all test specimens, constant water to cement ratio of 0.5 was used. The SF and MK were used as a replacement of cement in concrete. Firstly, crush aggregate and sand were mixed for about one minute then SF, MK and cement were added and the mixer was rotated for about 2 minutes.

Fig. 2: Metakaolin (MK)

Afterwards, 90 % of calculated water was poured and at the end remaining water with SP 470 plasticizer was poured. The concrete mixer was then rotated for another two minutes to get proper concrete mix.

The final mix was then casted in the specified moulds i.e. cylinders, prisms and cubes (300x300x300mm for HOH). The moulds were opened after 24 hours of casting for all specimens except HOH test cubes. The HOH test cubes were placed in a temperature-controlled curing tank for 10 days.

2.3 Concrete mix design

The control mix (CM) was prepared with no content of SF and MK, while in the remaining concrete mixes a constant 10% of SF was used with varying percentage of MK contents from 0-15%. The concrete mixes with the quantity of SF and MK are depicted in Table 3.

A total of sixty specimens were tested for each mix to investigate compressive, splitting tensile and flexural strength. The specimens were tested for curing age of 7, 14, 28 and 56 days. In addition to that, 10 cubes were tested for the heat of hydration. The details of test specimens with different curing age are depicted in Table 4.

2.4 Testing methods

2.4.1 Compression test

The cylindrical specimens of 300mm and 150mm in diameter were tested. The compression test was performed [11] for curing period of 7, 14, 28 and 56 days by 1000 kN capacity machine. The purpose of these tests was to determine the compressive strength behaviour of the test specimens at specified ages.

2.4.2 Splitting tensile test

The cylindrical specimens of 300mm and 150mm in diameter were tested. The splitting tensile test [12] was performed for different curing age of concrete i.e. 7, 14, 28 and 56 days.

2.4.3 Flexural test

The test specimen was of size 100x100x500mm. To determine the modulus of rupture [13] of concrete, the concrete prisms were tested at different curing periods.

2.4.4 Heat of hydration test

In concrete when we add water, an exothermic reaction takes place between cement and water. Due to exothermic reaction in concrete heat is generated which is called HOH in concrete [14]. In the current research, the HOH was found out using semi adiabatic approach. To determine the HOH, plywood cube filled with concrete mix were used. The cubes were internally insulated with 76.2mm thermopore sheet. The cubes that used for HOH measurement were of size 300x300x300mm. The test was performed for all mixes and temperature measurement was been done continuously for at least 10 days. A 'K' type thermocouple was inserted at the centre of concrete mix cube during casting. In total, ten specimens were tested for HOH measurement. The test arrangement used to measure HOH is shown in Fig. 3.

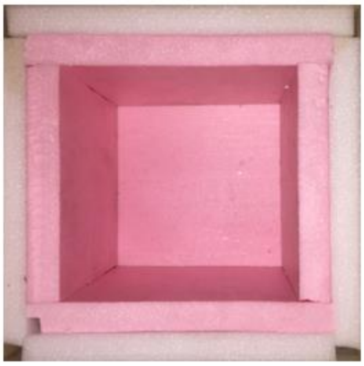
Temperature logger MS6514 and 'K' Type thermocouples were used for the test. The temperature logger was operated on battery and had data storage abilities. The thermo couples and temperature logger that used were made by Mastech®.

Table 3: Concrete mix design

Sr.#	Mix designation	Cement (%)	MK (%)	SF (%)
1	CM	100	0	0
2	S10M0	90	0	10
3	S10M5	85	5	10
4	S10M10	80	10	10
5	S10M15	75	15	10

Table 4: Test specimens details

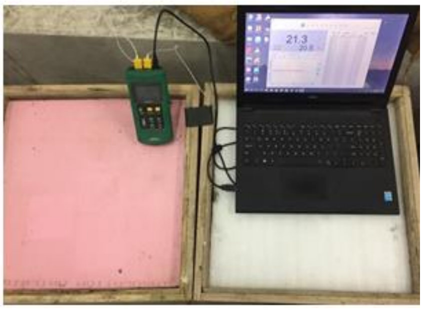
Test	Specimens (in)	Age (days)				Total specimens for each mix	Total for 5 mixes
		7	14	28	56		
Compressive Strength	Cylinder (6 × 12)	3	3	3	3	12	60
Splitting Tensile	Cylinder (6 × 12)	3	3	3	3	12	60
Flexural Strength	Beam (4 × 4 × 20)	3	3	3	3	12	60
Heat of hydration	Cube (12 x 12 x 12)	--	--	--	--	2	10



Plywood box with Thermopore Sheet

Temperature logger

'K' type thermocouples



Test Setup

Fig. 3: HOH Measurement Setup

3. Results and Discussion

3.1 Workability

The workability of concrete was measured according to ASTM [15]. At different levels of replacement of MK and SF, the workability of concrete is illustrated in Fig. 4. It can be observed from the figure that the control mix has a lower value of slump as compared to SF and MK concrete blends.

3.2 Compressive Strength

The outcomes of compression test specimens are depicted in Fig. 5. It is observed that the compressive strengths at 7, 14, 28 and 56 days were increased for all mixes except S10M15 mix. The maximum compressive strength achieved by S10M10 mix at 7, 14, 28 and 56 days is 12, 16, 27.5 and 29 MPa respectively.

3.3 Splitting tensile strength

It can be seen in Fig. 6 that the splitting tensile strength at 7, 14, 28 and 56 days is improved as compared to CM for all mixes. The trend of increase in splitting strength with the replacement of SF and MK is comparable in behaviour to compressive strength.

3.4 Flexural strength

The flexural strength results are shown in Fig.7. The Three-point loading test [13] was performed to find out the modulus rupture of the concrete. The maximum flexural strength is shown by S10M10 blend. The trend is similar to tensile and compressive strength results.

3.5 Heat of hydration test

By using semi adiabatic method, the heat of hydration was measured using a cube of sizes 300 x 300 x 300mm. This test was carried for all mixes and temperature measurement was performed for 10 days. Results were finalized by taking average values of test specimens. Temperature logger MS6514 and the thermocouples 'K' type were used for this test.

The values of peak temperatures, time and initial temperature values of every mix are given in Table 4. The trend of the heat of hydration changes for control mix and other mixes with SF and MK as shown in Fig. 8.

The maximum temperature rise of control mix was 38.95 °C at 17.25 hrs. The heat of hydration increased when SF was added in the mix and eventually the temperature of concrete is increased. The rise in HOH due to addition of SF was reduced by adding MK as it can be seen in Fig. 8. It is observed that more than 10% of MK quantity also cause the temperature rise in concrete. It is observed that S10M5 and S10M10 mix shows less HOH as compared to other mixes.

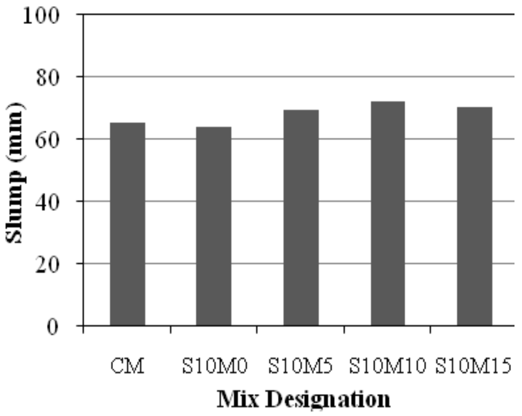


Fig. 4: Slump test results

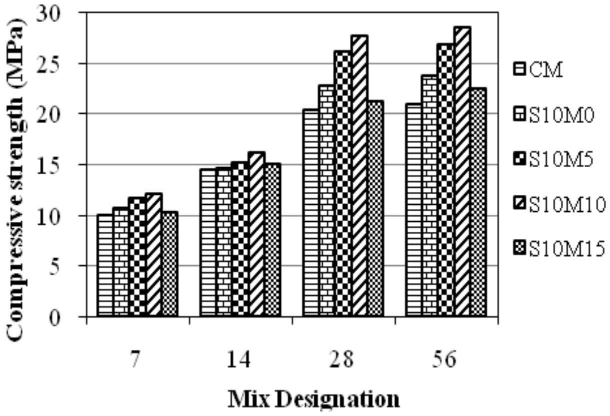


Fig. 5: Compressive strength results

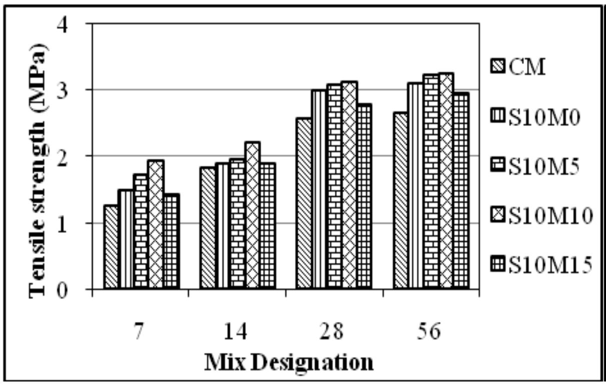


Fig. 6: Tensile strength w.r.t days

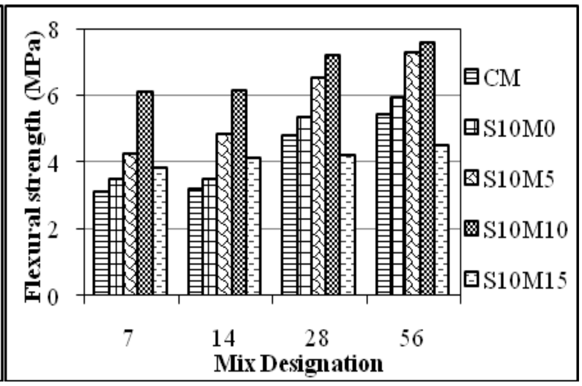


Fig. 7: Flexural strength w.r.t days

Table 4: Heat of Hydration results

Sr.#	Mix	Silica (%)	Metakaolin (%)	Peak temperature (ºC)	Time to peak (Hours.)	Initial temperature (ºC)
1	CM	0	0	38.95	17.25	22.5
2	S10M0	10	0	51.3	33.5	21.8
3	S10M5	10	5	34.7	10.5	23.1
4	S10M10	10	10	31.85	19	20.5
5	S10M15	10	15	41.05	40	29.4

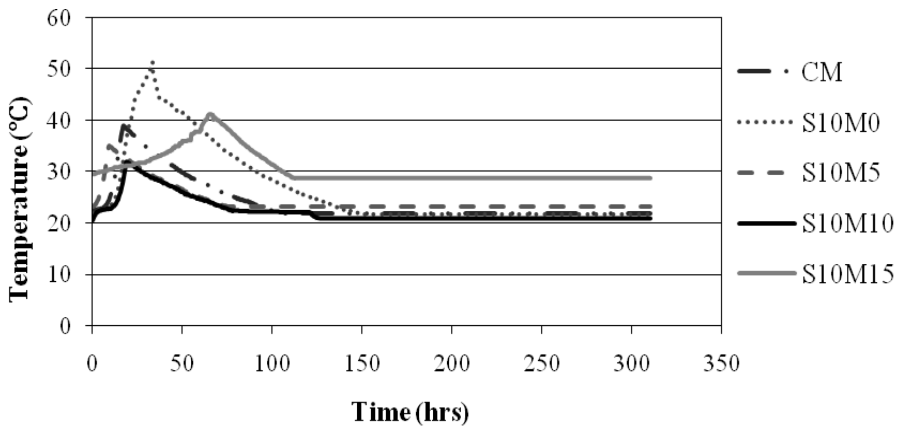


Fig. 8: Heat of hydration w.r.t Time

4. Conclusion

The workability, strength and HOH properties of concrete were investigated using SF and MK. Following results are deduced from the experiments:

- A large quantity of MK and SF in concrete causes the increase in slump value and consequently workability of concrete increases.
- For the given mix proportions MK and SF offer better workability when used as maximum 10% replacement; further rising the MK contents workability of concrete decreased.
- The compressive strength, tensile and flexural strength increases as compared to CM when the replacement of MK and SF was up to 10%. However, it has been observed that with the further increase of MK, strength was reduced.
- There is a rise in temperature of about 24 % in S10M0 mix as compared to CM mix. The incorporation of MK from 5-10% in concrete reduces the temperature approximately 38% as compared to SF concrete.
- The behaviour of the S10M10 concrete mix is almost superior from all concrete mixes in terms of HOH reduction and strength increase of concrete.
- The S10M10 mix has good early age and later day’s strengths as compared to all other mixes.
- The mix S10M10 results in optimum outcome for concrete mechanical properties i.e. compressive, tensile and flexural strength. It also has minimum heat of hydration among mixes.
- SF concrete with MK is recommended to use in those areas where higher early and later days strength with less HOH is required.

5. References

[1] Mehta, K.P. (2001). Reducing the environmental impact of concrete, *Concrete International*, 23(10), 61-66.

[2] Wang, J., Yan, P. (2013). Evaluation of early age mechanical properties of concrete in real structure. *Computers and Concrete,* 12(1), 53-64. doi:10.12989/cac.2013.12.1.053.

[3] Ding, J., Li, Z. (2002). Effects of metakaolin and silica fume on properties of concrete. *ACI Materials Journal*, 99(4), 393-398.

[4] Brooks, J.J., Johari, M. M. (2001). Effect of metakaolin on creep and shrinkage of concrete. *Cement and Concrete Composites*, 23(6), 495-502. doi:10.1016/S0958-9465(00)00095-0.

[5] Kadri, E., Kenai, S., Karim, E., Siddique, R., Schutter, G. (2011). Influence of metakaolin and silica fume on the heat of hydration and compressive strength development of mortar. *Applied Clay Science*, 53(4), 704-708. doi:10.1016/j.clay.2011.06.008.

[6] Poon, C.S., Kou, S.C., Lam, L. (2006). Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete.

Construction and Building Materials, 20(10), 858-65. doi:10.1016/j.conbuildmat.2005.07.001.

[7] Elaty, M.A.A. (2014). Compressive strength prediction of portland cement Concrete with age using a new model. *HBRC Journal*, 145-155. doi:10.1016/j.hbrcj.2013.09.005.

[8] Dinakar, P., Sahoo, P.K., & Sriram, G. (2013). Effect of metakaolin content on the properties of high strength concrete. *International Journal of Concrete Structures and Materials*, 7(3), 215-223.

[9] Langan, B.W., Weng, K.., Ward, M.A. (2002). Effect of silica fume and fly ash on heat of hydration of portland cement. *Cement and Concrete Research*, 32(7), 1045-1051. doi:10.1016/S0008-8846(02)00742-1.

[10] www.pagelpakistan.com/Pagel. 2019, accessed around 10/4/2019 at 1200PST.

[11] ASTM, C39/C39M-15a (2012). Standard test method for compressive strength of cylindrical concrete specimens. *ASTM International*.

[12] ASTM, C496 (2006). Standard test method for splitting tensile strength of cylindrical concrete specimens. *ASTM International*.

[13] ASTM, C78 (2002). Standard test method for flexural strength of concrete (Using Simple Beam with Third-Point Loading). *ASTM International*.

[14] Alhozaimy, A., Fares, G., Alawad, O.A., Al-Negheimish, A. (2015). Heat of hydration of concrete containing powdered scoria rock as a natural pozzolanic material. *Construction and Building Materials*, 81, 113-119. doi:10.1016/j.conbuildmat.2015.02.011.

[15] ASTM, C143 (2015). Standard test method for slump of hydraulic-cement concrete. *ASTM International*.