

Effect of Steel Fibers on Heat of Hydration and Mechanical Properties of Concrete Containing Fly Ash

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ABSTRACT

This study investigated the effects of steel fibers on the fresh and hardened properties, and heat of hydration of concrete containing FA (Fly Ash). A total of 192 samples were cast comprising cubes, cylinders, and prisms, for six concrete mixes with varying contents of steel fibers by volume and a fixed content of FA i.e. 15% by weight of cement. The semi adiabatic setup was used to monitor temperature rise due to the heat of hydration in the concrete mixes for fourteen days. The use of FA increased workability, and decreased early compressive strength, tensile strength and heat of hydration of concrete. However, an increase in the compressive strength of FA concrete was observed by the addition of steel fibers up to 0.9% whereas a consistent increase in the splitting tensile strength and modulus of rupture was observed with the addition of the steel fibers from 0.4-1.8%. Further the test results showed that increasing steel fibers content decrease the evolution of heat due to hydration. It was concluded that the FA concrete with steel fibers can be used in precast industry and mass construction projects due to the improved mechanical properties and lower heat of hydration.

Key Words: Heat of Hydration, Fly Ash, Steel Fibers, Mechanical Properties of Concrete, Semi Adiabatic.

1. INTRODUCTION

Concrete is a widely used material in the world for construction work and it mainly consists of aggregates, cement, water and admixtures. To produce large amount of concrete, a significant quantity of Portland Cement is required, which in turn produces about 7% of gasses globally [1]. To reduce the impact on the environment, researchers are making efforts to produce environment friendly and economical concrete by replacing cement with supplementary materials i.e. FA, slag and other industrial wastes [2-3]. In normal and high strength concrete low calcium FA

(ASTM Class-F) has been widely used [4]. The use of FA in concrete has positively affected the mechanical and durability properties of concrete [5]. In the study of Malhotra [6] it was reported that FA has shown excellent durability properties against sulphate attack, and freezing and thawing cycles. In the study of Chindaprasirt et. al. [7] it was observed that drying shrinkage of the FA concrete was significantly reduced. The sorptivity of concrete reduced by the replacement of cement with FA [8]. In the study of Naik et. al. [9] it was observed that FA concrete has given better result

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in air and water permeability than Portland cement concrete. The Government of Pakistan has planned to generate about 8880 MW of electricity [10] by burning locally available coal, which will produce millions of tons of FA as a waste. Therefore, the replacement of cement with FA will make positive impact on the environment and economy of Pakistan. Moreover, by using FA concrete, the heat of hydration can also be controlled [11] which evolved rapidly when the dimensions of the cast concrete are smaller. However, in the case of mass concrete construction, such as raft foundation, bridges and dams, heat of hydration does not dissipate too quickly which causes the development of internal temperature. The temperature difference between internal and outer surfaces induces the thermal stresses, which may be greater than the tensile capacity of concrete causing thermal cracks in the concrete [12-14]. Internal micro cracks may also be developed due to the heat of hydration in concrete [15].

Among different Pozzolanic materials, the FA has been proved to be one of the good materials which can control heat better as compared to other supplementary materials [16-17]. However, a decrease in early strength can be observed in concrete where cement is replaced with FA [18]. Therefore, it becomes important generally, to improve early strength of concrete containing FA, for example, to make possible its use in pre-cast industry or in colder regions where formwork strips delay the further construction. Other supplementary materials like Silica Fume can improve the early strength of concrete but it will affect durability of concrete [19].

In some studies, it was observed that the addition of polypropylene and steel fibers improves the mechanical properties of concrete [20-22]. In constant w/b (water binder) ratio concrete which contains FA and steel fibers,

the compressive strength increases when the steel fibers are increased up to 1% and further increase in steel fibers reduces the compressive strength [23]. Generally, more literature is available on the studies carried out to observe the individual effects of FA or steel fibers on the

mechanical properties of concrete [24-25]. However, the experimental data is scarce on the use of FA along with steel fibers in the concrete with other locally available concrete materials of Pakistan to observe their combined effect on concrete early day's strength and heat of hydration. Therefore, the aim of this research is to study the effect on heat of hydration, early strength characteristics, fresh and hardened properties of the concrete containing FA with varying contents of steel fibers.

2. EXPERIMENTAL PLAN

The experimental plan includes casting of the concrete specimens, measurement of heat of hydration using semi-adiabatic arrangement and determination of fresh and hardened concrete properties comprising workability, compressive strength, splitting tensile strength, modulus of rupture and permeability tests. A total of 192 samples were cast, comprising of 72 cubes (150x150x150 mm) for compressive strength tests, 72 cylinders (150mm diameter, 300mm height) for splitting tensile strength tests, 18 cylinders (100mm diameter, 150mm height) for permeability tests, 18 prisms (100x100x500mm) for modulus of rupture tests and 12 cubes (300x300x300 mm) for heat of hydration measurements.

3. MIX DESIGN AND DESIGNATIONS

A total of six concrete mixes were prepared for the study. The control mix was prepared considering no replacement

either with FA or steel fibers. The cement content was replaced 15% by weight with the FA in five of the mix types since 15% replacement by weight provided optimum strength properties of the hardened concrete [22]. The steel fibers had varying contents (0.4, 0.9, 1.5 and 1.8% by volume of concrete) in the four mix types. The w/b ratio and SP (Superplasticizer) by weight of binder were kept constant at 0.38 and 1.4% respectively in all the mix types. The detail of the mix design is given in Table 1. The control mix which contains neither FA nor steel fibers is designated as OPC (Ordinary Portland Cement) while the mix containing 15% FA only as FA 15. The rest of the four mixes with 15% FA and varying contents of steel fibers by volume of concrete i.e. 0.4, 0.9, 1.5 and 1.8% are designated as ST0.4, ST0.9, ST1.5, ST1.8 respectively. The details of mix designation are given in Table 2.

4. MATERIALS

The properties of the materials used in the preparation of the concrete mixes are provided in the following paragraphs. For this study locally available Lawrencepur brand sand was used as fine aggregate. The water absorption and specific gravity of sand was 1.21 and 2.71% respectively (ASTM-C 128-15). Whereas, the fineness modulus of sand was found to be 2.49 (ASTM-C136-06). The locally available Margalla

crush was used as CA (Coarse Aggregate) which has nominal size of 20mm (ASTM-C136-06) and specific gravity of 2.66 (ASTM-C127-07). Moreover, the properties and gradation of aggregates (Fine and CAs) are also given in Tables 3-4 respectively. OPC Type-1 cement conforming to ASTM C-150 having compressive strength of 40.68MPa and specific gravity of 3.15 was used. The properties of cement are also given in Table 5. For partial replacement of cement ASTM C 618 FA was used in the study. The low calcium FA with particle size 25% retained on 45-micron sieve, Class-F (Fig. 1) was obtained from Dirk® and the detailed properties [26] of FA are given in Table 6. The commercially available Dramix 65/35 BG steel fibers having both ends hooked were used.

The steel fibers as shown in Fig. 2, have tensile strength, length, diameter and aspect ratio of 1100MPa, 35, 0.55 and 65 respectively which conform to ASTM A820. The

TABLE 2. MIX DESIGNATION

Mix ID	Mix Composition
OPC	Control Mix
FA15	15% FA
ST0.4	15% FA+0.4% Steel Fibers
ST0.9	15% FA+0.9% Steel Fibers
ST1.5	15% FA+1.5% Steel Fibers
ST1.8	15% FA+1.8% Steel Fibers

TABLE 1. MIX PROPORTIONS FOR ONE CUBIC METER OF CONCRETE (kg/m³)

Mix ID	Cement (kg/m ³)	Fly Ash (%)	Fly Ash (kg/m ³)	Steel Fibers (%)	Steel Fiber (kg/m ³)	Sand (kg/m ³)	Coarse Aggregates (kg/m ³)	Water Binder	Water (kg)	Superplasticizer (%)	Coarse Superplasticizer (kg/m ³)
OPC	462	-	-	-	-	600	1339	0.38	176	1.4	6.5
FA15	393	15	69.3	-	-	600	1339	0.38	176	1.4	6.5
ST0.4	393	15	69.3	0.4	31.4	600	1339	0.38	176	1.4	6.5
ST0.9	393	15	69.3	0.9	70.7	600	1339	0.38	176	1.4	6.5
ST1.5	393	15	69.3	1.5	117.8	600	1339	0.38	176	1.4	6.5
ST1.8	393	15	69.3	1.8	141.3	600	1339	0.38	176	1.4	6.5

super-plasticizer SP 470 (Ultra Chemicals®) was used in the study to maintain only workability of concrete. A constant 1.4% of SP by weight of binder was used in all the concrete mixes to neglect any effect on the strength and heat of hydration. The SP 470 was brown in color with specific gravity of 1.155. The water used for mixing concrete ingredients was ordinary tap water of the concrete laboratory having pH.7, chloride 240 mg/l, sulphate 45 ppm and hardness 300 mg/l.



FIG. 1. FLY ASH USED IN THE STUDY

TABLE 3. PROPERTIES OF AGGREGATES

Coarse Aggregate		Fine Aggregate (sand)	
Specific Gravity	2.66	Specific Gravity	2.71
Water Absorption	0.8%	Water Absorption	1.21%
Moisture Content	1.0%	Fineness Modulus	2.49

TABLE 4. GRADATION OF AGGREGATES

Gradation of Sand		Gradation of Coarse Aggregate	
Sieve	Finer than Sieve (%)	Sieve	Finer than Sieve (%)
3/8 in.	100	1 Inch	100
# 4	98.10	3/4 Inch	95.13
# 8	92.90	3/8 Inch	35.46
#16	79.90	3/16 Inch	02.67
#30	54.50	-	-
#50	20.30	-	-
#100	05.40	-	-

TABLE 5. CHEMICAL AND PHYSICAL PROPERTIES OF CEMENT

Chemical Composition		Physical Properties	
SiO ₂ (%)	22.0	Specific Surface	322 m ² /kg
Al ₂ O ₃ (%)	5.50	Consistency	30%
Fe ₂ O ₃ (%)	3.50	Initial setting time	1hr, 42min
CaO (%)	64.25	Final setting time	3hr, 55min
MgO (%)	2.50	Soundness	No Soundness
SO ₃ (%)	2.90	Specific gravity Compressive 40.68 MPa Strength	3.15
Na ₂ O (%)	0.20		
K ₂ O (%)	1.00		
LOI (%)	0.64		

5. MIXING, CASTING AND CURING

The concrete mixes were prepared in tilting drum type mixer by dry mixing sand and CA at first for one minute. Then binder (cement and/or FA) and steel fibers were added to the already mixed sand and CA, and mixed for another two minutes. Almost 90% of the required water was then added and mixed for further one minute to make it a homogeneous mixture. Finally, SP and the remaining water were added and mixed for two more minutes to get the desired concrete mix. The well mixed concrete was cast into cubes, cylinders and prisms moulds which were demoulded after 24 hours of casting. All concrete samples i.e. FA, OPC and steel fiber reinforced concrete were cured from 3-28 days. The cuboids for measuring heat of hydration in concrete were also cast at the same time and the temperature was recorded for 14 days.

6. METHODOLOGY TO DETERMINE HEAT OF HYDRATION

The heat of hydration in concrete is the result of reaction of cement with water. In this study, semi- adiabatic

TABLE 6. PROPERTIES OF FLY ASH

Loss on Ignition (%)	1.53
Chloride (%)	0.011
Sulphate (%)	0.51
Free CaO (%)	Nil
Reactive CaO (%)	4.06
Total CaO (%)	4.42
SiO ₂ (%)	51.55
Al ₂ O ₃ (%)	33.32
Fe ₂ O ₃ (%)	3.34
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ (%)	88.21
Na ₂ O (%)	0.51
MgO (%)	0.75
Phosphate (as P ₂ O ₅) mg/kg	6.22

arrangement [27-28] has been used for the measurement of the heat in concrete. For this purpose, cuboids made up of plywood sheets internally lined with 76 mm thick polystyrene sheet, acting as insulator, are prepared. The inner dimensions of the cuboids are 300x300x300 mm. The arrangement of the measurement of the heat is shown in Fig. 3(a-d). The plywood sheets and polystyrene edges were waterproofed with the water sealant. For each type of concrete mix, two such cuboids were cast, hence a total of 12 such samples were prepared. A thermocouple of k type, connected with the temperature logger (battery operated and have data storage capabilities), was inserted in the center of the cuboids for measuring the heat of hydration. The data loggers and thermocouples are manufactured by Mastech®.

7. RESULTS AND DISCUSSION

7.1 Workability

To determine the consistency of fresh concrete, slump test was carried out according to ASTM C143M - 15a. The slump test results are presented in Fig. 4. It can be seen that when the cement is replaced with FA the slump of concrete has increased as compared to the control mix.

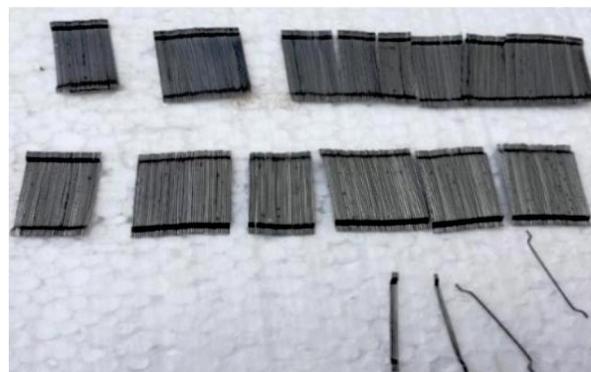


FIG. 2. HOOKED 65/35 BG STEEL FIBERS

The ball bearing effects due to the spherical shape of FA particles increases the workability of concrete. These spherical shaped FA particles reduces the internal friction of fresh concrete, thus increase the fluidity of concrete [29]. The specific gravity of cement is higher than the FA, and, when cement is replaced weight to weight with FA, it causes increase in binder (paste) volume of concrete that govern workability of concrete [30]. The slump test results also show that when steel fibers contents are increased in the concrete the slump values decreased. It can be concluded that the workability of concrete is decreased due to the steel fibers addition. Steel fibers hinder the flow of concrete thus causing lower workability of concrete.

Some other studies have also shown a decrease in workability of concrete with steel fibers addition [22].

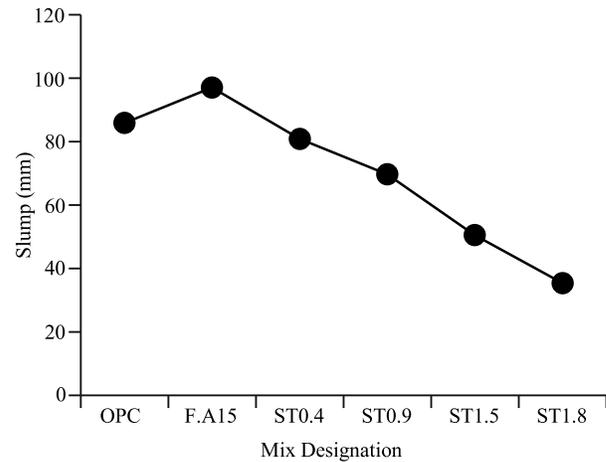


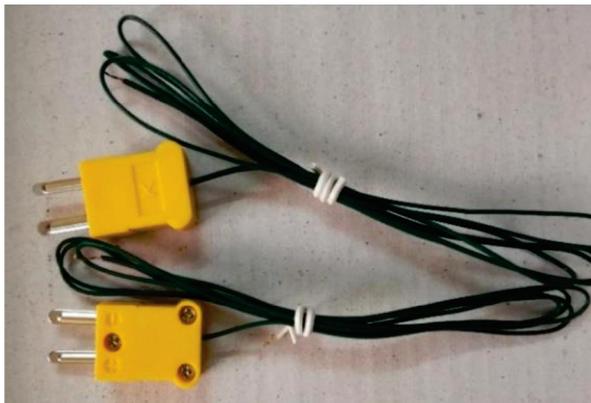
FIG. 4. THE VARIATION IN THE SLUMP OF CONCRETE MIXES



(a) PLYWOOD CUBOID BOX



(b) CUBOID LINED WITH 76 MM POLYSTYRENE



(c) TYPE K THERMOCOUPLES FROM MASTECH®



(d) COMPLETE SETUP FOR HEAT OF HYDRATION MEASUREMENT

FIG. 3. SETUP FOR HEAT OF HYDRATION MEASUREMENT

7.2 Compressive Strength

The compressive strength of concrete was calculated at the age of 3, 7, 14 and 28 days according to BS EN 12390-2:2009. The compression test was carried out in compression testing machine of 3000 kN capacity. The compressive strength was calculated by taking average of three samples. The results of compressive strength tests are presented in Fig. 5 and Table 7. It can be seen that in FA15 concrete mix the 3 days compressive strength decreased as compared to the control mix (OPC). These results confirm the previous literature [18]. Almost 37% of 3 days compressive strength has decreased for FA15 mix as compared to the OPC. It can be observed that with the addition of 0.4% steel fibers into FA concrete the early compressive strength (3 days) increased 38.5 and 2.4% as compared to FA15 mix and OPC mix respectively. In ST0.9 concrete mix the 3 days compressive strength is higher than the OPC concrete and FA15 concrete mix. The 28 days strength of ST0.9 is also higher than all the other mix types except OPC mix.

It can be inferred that FA concrete compressive strength is increased with the addition of steel fibers up to 0.9% and further increase in fibers ratio i.e. from 1.5-1.8%, decreases the compressive strength. The increase in the compressive strength with the addition of steel fibers i.e. for 0.4 and 0.9% was due to the uniform dispersion of steel fibers and due to crack closing capacity of steel fibers. These results

are in line with the previous study by Siddique and Kaur [31]. The decrease in compressive strength when the steel fibers are increased from 1.5-1.8% may be due to the non-uniform dispersion of steel fibers which may cause non-uniformity of the mix. Another study had reported inadequate compaction of the concrete due to that much increase in the steel fibers [30].

7.3 Splitting Tensile Strength

The splitting tensile strength of cylinders having diameter 150mm and height 300mm was carried out at the age of 3, 7, 14 and 28 days, according to ASTM C 496/ 496M – 04. The results of splitting tensile strength are presented in Fig. 6. From Fig. 6(a) it can be observed that with the increase of age the tensile strength of all concrete mixes increased

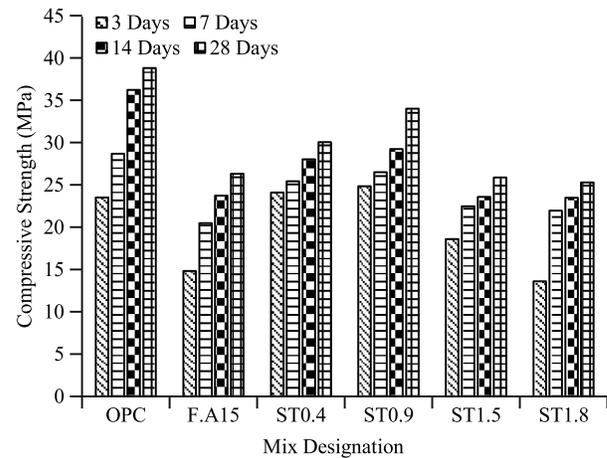


FIG. 5. THE VARIATION OF COMPRESSIVE STRENGTH WITH THE AGE OF CONCRETE MIXES

TABLE 7. COMPRESSIVE STRENGTH (MPa)

Mix	3 Days	7 Days	14 Days	28 Days
OPC	23.55	28.72	36.26	38.84
FA15	14.83	20.49	23.77	26.35
ST0.4	24.12	25.46	28.04	30.09
ST0.9	24.86	26.55	29.27	34.03
ST1.5	18.6	22.51	23.61	25.89
ST1.8	13.6	21.97	23.48	25.31

consistently. The FA15 mix early strength (3 days) is lowered as compared to the other mixes. These results also match with the results of previous literature [18]. At the age of 28 days the concrete tensile strength of ST1.8 is higher than all the other mixes, this is due to the high contents of steel fibers in the concrete mix.

It can be seen in Fig. 6(b), when steel fibers ratio was increased in FA concrete, the tensile strength increases consistently; the increase in strength is the influence of steel fiber arresting cracking [31]. It can be concluded that when the steel fibers are increased from 0.4-1.8%, an increase of 56 and 44% are observed in the 28 days tensile strength as compared to the FA15 mix and OPC mix respectively. These results of splitting tensile strength corresponds to the study by Guneyisi and Gesoglu [33].

7.4 Flexural Strength

For determining flexural strength of the concrete mixes, third point loading test was carried out to calculate MOR (Modulus of Rupture) of the prism specimens (100x100x500mm) according to ASTM C78/C78M-16. An average of three the specimens test results was considered

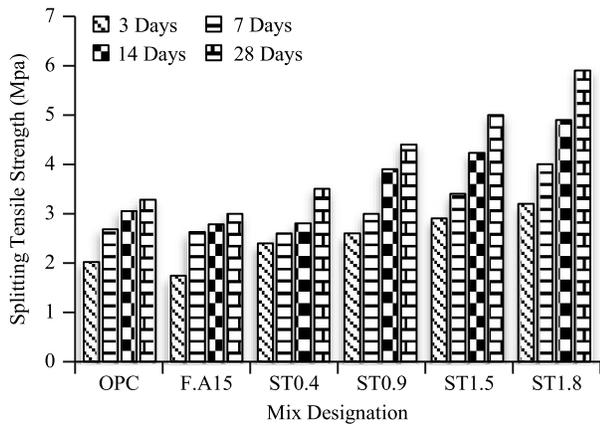


FIG. 6(a). THE VARIATION OF SPLITTING TENSILE STRENGTH WITH THE AGE OF CONCRETE MIXES

for the MOR value. The results of MOR are presented in Fig. 7. It can be observed that the MOR of FA15 mix is lower as compared to the other concrete mixes. The ST1.8 mix results in the largest value of MOR, which can be attributed to the effect of the steel fibers arresting cracking [21].

The MOR graph suggests that as the steel fibers ratio is increased, the flexural strength of the concrete will increase. A 45% increase in the MOR value is observed when the steel fibers ratio is increased from 0.4-1.8% as compared to the FA15 mix.

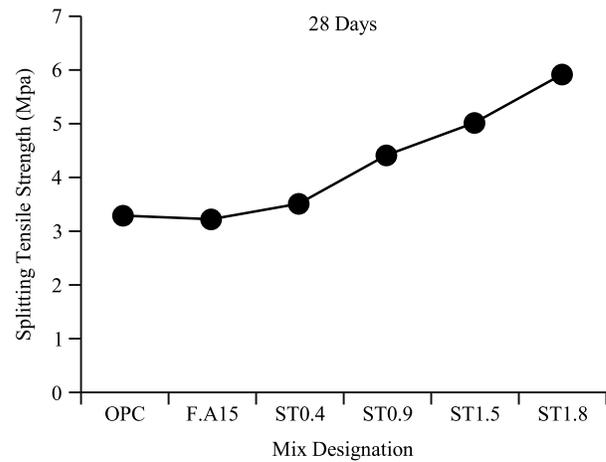


FIG. 6(b). THE VARIATION OF SPLITTING TENSILE STRENGTH WITH THE RATIO OF STEEL FIBERS IN FA CONCRETE MIXES

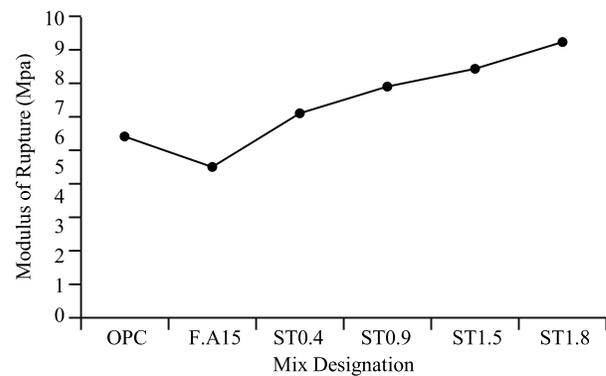


FIG. 7. THE VARIATION OF MOR VALUES IN THE CONCRETE MIXES

7.5 Permeability of Concrete

Permeability is an important property to observe the porosity of concrete. The results of the permeability test are shown in terms of depth of water that had penetrated in the cylindrical concrete samples of 100mm diameter and 150mm height according to BS EN 12390-8:2009. The penetration of water in concrete is depicted in Fig. 8 and the results of water permeability are presented in Fig. 9.

It can be observed in Fig. 9 that penetration depth of water for OPC and FA15 mix is almost same. However, when the steel fibers are added the penetration depth of water is



FIG. 8. PENETRATION OF WATER IN FA STEEL FIBERS REINFORCED CYLINDER

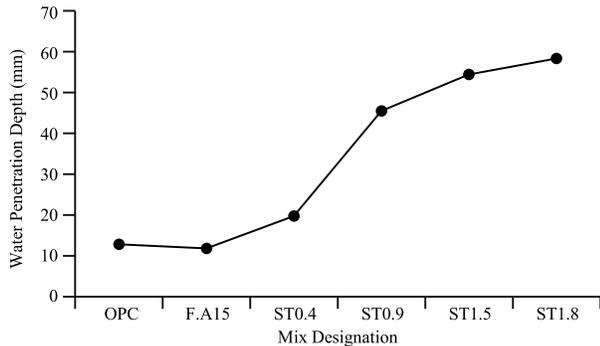


FIG. 9. THE VARIATION OF WATER PENETRATION DEPTH IN CONCRETE MIXES

increased. Hence, it can be inferred that by the addition of the steel fibers the porosity of the concrete mix will increase which is in line with the study by Hwang and Kim [34]. The durability properties may be affected by the addition of high steel fiber contents in FA concrete due to increased porosity, and concrete can be susceptible to chloride and sulphate attacks.

7.6 Measurement of Heat of Hydration

The heat of hydration is produced as a result of a series of exothermic chemical reactions taking place in the concrete. The temperature rise due to the heat produced in the concrete mix with respect to the time (hours) is shown in Fig. 10. The Initial temperature, peak temperature and the time to reach peak temperature for all the mixes are shown in Table 8. The temperature was monitored till 332 hours (14 days) after casting. There is not a significant rise in the temperature in the first 3.5-4 hours after casting of the concrete. This is termed as dormant period in which very less heat is evolved.

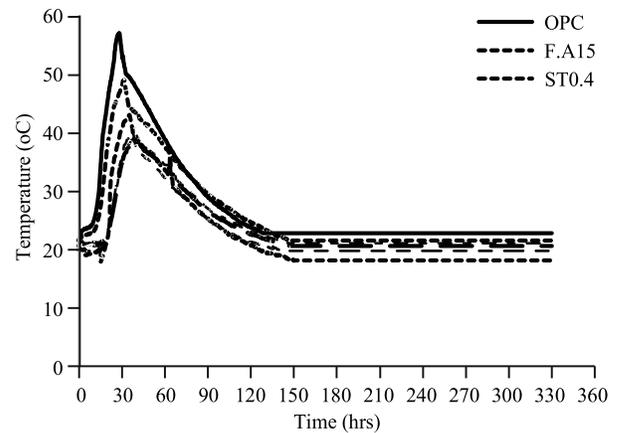


FIG. 10. COMPARISON OF THE TEMPERATURE RISE DUE TO THE HEAT OF HYDRATION IN THE-CONCRETE MIXES WITH TIME

TABLE 8. SUMMARY OF MEASUREMENT OF TEMPERATURE RISE DUE TO THE HEAT OF HYDRATION IN THE CONCRETE MIXES

Description	OPC	FA 15	ST 0.4	ST 0.9	ST 1.5	ST 1.8
Initial Temperature (°C)	21.6	21.6	20.01	20.01	21.15	20.65
Peak Temperature (°C)	57	48	43	41	40	39
Time at Peak Temperature (h)	29	32	35.75	37	40	42

After the dormant period a rapid heat evolution occurred which continues till the peak temperature is achieved. The initial temperature development for all mixes is nearly same in the dormant period where the temperature variation is negligible. It can be observed in Table 8 that the OPC mix has evolved more heat as compared to the other mixes which have FA and steel fibers. These high temperature results of OPC mix comply with the results of the other studies [27,35]. The OPC mix had achieved peak temperature of 57°C after 28 hours of casting while in the FA 15 mix, the peak temperature of 48°C was achieved after 32 hours of casting. Hence, the difference in the peak temperature is 9°C. The peak temperature of ST0.4 mix was 43°C achieved after 35.75 hours.

The other mixes i.e. ST0.9, ST1.5, and ST1.8 have achieved the peak temperatures of 41, 40, 39°C after 37, 40, and 42 hours respectively. It can be inferred that when the steel fibers ratio is increased the peak temperature is 5°C less than the FA15 mix and the time to reach this peak temperature has also been increased. The low temperature development in FA concrete with steel fibers, can be due to the increase in porosity of the concrete after the addition of steel fibers which may have allowed the easy transfer of heat to the other parts of the specimen from the center of the cast cuboid (i.e. from the insertion point of the thermocouple).

8. CONCLUSION

Based on the results described above following conclusions can be drawn:

(i) The workability of concrete increased by 11.5% by the replacement of 15% cement with FA in concrete. The workability of FA concrete decreased by about 63% when the steel fibers are increased from 0.4-1.8% by volume of concrete.

(ii) The replacement of 15% FA in concrete decreased early compressive strength (3 days) by 37% as compared to OPC mix whereas the addition of steel fibers from 0.4-0.9% in the FA concrete increased the same by about 38.5% as compared to FA15 mix and 2.4% as compared to OPC mix. The addition of steel fibers above 0.9% in FA concrete causes reduction in early strength. It can be observed from the results that up to 0.9% addition of steel fibers provided optimum values for 3 and 28 days compressive strength and further addition causes reduction in compressive strength and workability.

(iii) The early (3 days) splitting tensile strength of FA15 mix decreased as compared to OPC mix. After the addition of steel fibers to FA concrete from 0.4-1.8%, the early splitting tensile strength increased by about 46% as compared to FA15 mix. The increase in splitting tensile strength at 28 days was also observed with the increase of steel fibers.

(iv) The modulus of rupture is decreased with the addition of FA in concrete. However, by increasing the steel fibers in FA concrete the modulus of rupture increased.

(v) The value of permeability is nearly the same in OPC and FA.15 mixes. However, after the incorporation of the steel fibers to FA concrete, the permeability has increased. Due to increase in permeability the durability properties of FA concrete may negatively be affected, so it can be suggested to use higher amount of FA for better durability properties.

- (vi) The peak temperature rise due to the heat of hydration is 15.7% less in FA15 mix as compared to the OPC mix. A decrease of 18.75% in the peak temperature is observed in ST1.8 from FA15 mix. Almost 32% decrease in the peak temperature in ST1.8 mix can be observed as compared to OPC mix. Hence, the addition of steel fibers reduces the peak temperature due to the heat of hydration or in other words the heat will be evolved slowly when the steel fibers are added to the FA concrete.
- (vii) Based on this study, a 0.9% steel fibers by volume in FA concrete is recommended for mass concrete and precast concrete.
- (viii) Therefore, it can be concluded that the steel fibers with FA can be used in precast industries and mass construction due to the improved mechanical properties and the lower heat of hydration.

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