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# STUDY OF CROSSOVER EFFECT IN COMPRESSIVE STRENGTHOF CEMENT-BASED MATERIALS CONTAINING SUPPLEMENTARY CEMENTITIOUS MATERIALS

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**Article Info**



**Abstract**

In cement-based materials (CBMs), cement hydration process and resulting compressive strength depend on their mix composition, curing temperature, curing methods and curing duration. The strength-gaining rate and hardening process of CBMs under normal curing regimes are slow. Therefore, accelerated curing techniques are applied for gaining high early-age strength. CBMs subjected to an initial high curing temperature undergoes accelerated hydration resulting in non-uniform scattering of the hydration products. It creates a great porosity and reduction in compressive strength at later ages. This phenomenon is called crossover effect (COE). Currently, the use of supplementary cementitious materials (SCMs) is becoming mandatory due to economic, environmental and sustainable issues. In this research, compressive strengths of mortar samples having 30% and 50% of fly ash (F-ASH), ballast furnace slag (GSP), ground and treated palm oil fuel ashes (GPA and TPA) in replacement of conventional Portland cement (CPC) were determined under accelerated curing conditions of HWC and HAC in short and long terms. The data obtained demonstrated that COE was observed in CPC control and blended mixes from 56 to 150 days; however, it was less than 10% for all of these mixes.

**Keywords:**

*cement-based materials; supplementary cementitious materials; crossover effect; accelerated curing; compressive strength*

## INTRODUCTION

The most widely used building materials in construction are cement-based materials (CBMs) including paste, mortar and concrete [1, 2]. In these materials, cement hydration is very exothermic [2]. Conditional on the amount of water in the mix and curing temperature situations, the cement hydration process can continue for many years at a decreasing trend [2, 3]. High curing temperatures of CBMs speed up the rate of strength acquisition in the short term but slow down the strength in the long term [4].

Under typical curing circumstances, the strength gain and hardening of CBMs is slow [1, 3]. Consequently, rapid curing techniques are used to provide high early-age strength, particularly in the prefabrication sector [3] . At beginning CBMs face rapid hydration when exposed to a high curing temperature causing the hydration products to disperse unevenly [5]. Early acquaintance results in lower porosity, whereas later exposure results in higher porosity [6]. At early-age, it leads to higher compressive strength, while later-age, it causes lower compressive strength called crossover effect (COE) in compressive strength [5, 6]. COE is the mechanism that lowers CBMs' ultimate compressive strength [3, 4].

Conventional Portland cement (CPC) has often been replaced by supplemental cementitious materials (SCMs), such as fly ash (F-ASH), ballast furnace slag (GSP), and palm oil fuel ash (POF-ASH) [6]. Because of its pozzolanic qualities, F-ASH is frequently used as SCM to replace CPC [6, 7]. By lowering permeability, F-ASH resist chloride penetration and sulfate attack [8]. F-ASH gradually increases strength even if it may have a lower initial strength due to ongoing pozzolanic process [9]. The Class F F-ASH taken in this study has a low calcium concentration (less than 10%) and high pozzolanic qualities, often used for a variety of applications [10].

Finely grinded GSP was used in place of CPC in this study. GSP is quickly slaked with water to become glassy and reactive, which lowers the heat of hydration, reducing the risk of thermal cracking, especially in massive concrete structures and increases later-age strength [11]. GSP can contribute to higher compressive strength in mortars, especially when used in combination with other SCMs [11]. Using GSP promotes sustainable construction practices utilizing a waste product from the steel industry and reducing reliance on traditional CPC production [12]. In addition, it has smaller environmental footprint than CPC, contributing to more sustainability in construction [10].

Finely crushed POF-ASH has pozzolanic qualities and can be used as SCM in place of CPC. POF-ASH decreases mortar voids and increases its density [12]. Additionally, POF-ASH makes CBMs more cohesive [13]. POF-ASH enhances resistance to sulfates and chlorides while decreasing permeability [14]. Porosity and permeability are eventually decreased by the filling of cavities by finer POF-ASH particles [15]. Since POF-ASH is a result of burning biomass from palm oil in power plants which ultimately reduces industrial waste [16].

Higher early-age strength can result from the addition of SCMs such as F-ASH, GSP, silica fume, and POF-ASH to a cement mix [17]. At higher curing temperatures, a considerable enhancement of the pozzolanic reaction of SCMs is observed [18]. Nevertheless, if the curing temperature is too high or excessive, the pozzolanic reaction may become less effective and eventually have a lower final strength [19].

In this research, compressive strengths of mortar samples having 30% and 50% of F-ASH, GSP, ground and treated POF-ASH (GPA and TPA) in replacement of CPC were determined in short and long terms. The data obtained demonstrated that COE was observed in CPC control and blended mixes from 56 to 150 days; however, it was less than 10% for all of these mixes.

## 2. Experiments

### 2.1 Materials

All of the mixtures comprised CPC having a specific gravity of 3.12. According to the Bernauer, Emmett, and Teller (BET) test, CPC's specific surface area (SSA) was 2667 m2/kg. The maximal particle size was 4.75 mm. The local mining sand had a specific gravity of 2.68. Class F F-ASH (F-ASH) used in this study had a specific gravity of around 2.29. The color of F-ASH was yellowish-grey. The BET test revealed that the SSA of F-ASH was 2858 m2/kg. The specific gravity of ground granulated ballast furnace slag (GSP) was around 2.83. GSP was off-white in color. The SSA of GSP was 3197 m2/kg according to the result of BET test.

This study employed ground and treated POF-ASH (GPA and TPA). Raw POF-ASH was taken from Selangor state Malaysia. Raw POF-ASH was dried out by heating it for 24 hours at 105 ± 5 °C in an oven. A 300 mm sieve was used to remove the coarse POF-ASH remainders. To reduce the particle size, a Los Angeles machine crushed this POF-ASH (Awal and Hussin, 1997; Safiuddin, Abdus Salam, & Jumaat, 2011). 6–8 kg of POF-ASH was ground by the machine's electric motor, which was designed to operate for 16 hours at 33 rpm. To lessen its loss on ignition (LOI), POF-ASH was then heated to 600 °C for two hours. Further grinding was done to produce even finer POF-ASH particles. According to the BET test, GPA and TPA had SSAs of 4940 m2/kg and 7400 m2/kg, respectively. It was determined that specific gravity of GPA and TPA was 1.81 and 1.98, respectively. Table 1 demonstrates the physical characteristics of the materials utilized in this study.

**Table 1: Physical characteristics of materials used**

| **Property** | **Sand** | **CPC** | **F-ASH** | **GSP** | **GPA** | **TPA** |
|---|---|---|---|---|---|---|
| **Color** | White | Grey | Whitish grey | Off-white | Dark grey | Grey |
| **Specific surface area (SSA) according to BET test ($m^2$/kg)** | - | 2667 | 2858 | 3197 | 4940 | 7400 |
| **Specific gravity** | 2.68 | 3.12 | 2.29 | 2.83 | 1.81 | 1.98 |

To create blended cement mortars with appropriate workability, the superplasticizer (SP) was used. It was an aqueous solution composed of modified polycarboxylate copolymers, which had a density of 1.09 kg/m3. The amount of SCM replacement determines the amount of SP in the mortar. The samples were mixed and cured using water from the lab's pipeline. The samples of CPC, sand, F-ASH, GSP, GPA and

TPA are shown in Figure 1. Using X-ray fluorescence spectrometry, the chemical composition of CPC, F-ASH, GSP, GPA, and TPA was ascertained and is provided in Table 2.




CPC Mining sand F-ASH GSP


GPA TPA

**Table 2: Chemical composition of CPC, F-ASH, GSP, GPA and TPA (% by mass)**

| Chemical name | CPC | F-ASH | GSP | GPA | TPA |
|---|---|---|---|---|---|
| **CaO** | 60.68 | 12.78 | 40.88 | 5.78 | 5.03 |
| **$SiO_2$** | 20.46 | 40.10 | 35.98 | 59.15 | 69.05 |
| **$Al_2O_3$** | 3.86 | 17.05 | 13.47 | 3.74 | 4.01 |
| **$Fe_2O_3$** | 3.38 | 15.05 | 0.43 | 6.35 | 4.35 |
| **MgO** | 3.10 | 6.68 | 5.42 | 4.88 | 5.20 |
| **$P_2O_5$** | 0.06 | 0.20 | 0.01 | - | - |
| **$TiO_2$** | 0.17 | 0.88 | 0.63 | - | - |
| **$K_2O$** | 0.26 | 1.05 | 0.36 | 8.24 | 7.01 |
| **$SO_3$** | 2.20 | 0.63 | 1.75 | 0.72 | 0.41 |
| **SrO** | 0.03 | 0.07 | 0.05 | - | - |
| **MnO** | 0.15 | 0.21 | 0.20 | - | - |
| ***LOI** | 2.23 | 0.70 | 0.72 | 16.1 | 2.1 |

*LOI = Loss on Ignition

## 2.2 Mix proportions

A control mortar using a w/b ratio of 0.48 and a c/s ratio of 1:3 was prepared. Then 50% of F-ASH, GSP, TPA, and GPA by weight was used in place of the CPC using a w/b ratio of 0.48 and a c/s ratio of 1:3. The F-ASH-50, GSP-50, GPA-50, and TPA-50 were the new mixes' names. To get the same flow of TPA -50 mix, the w/b was maintained at 0.78.

**TABLE 3: Mix proportions of Control and 50% replacement of SCMs with CPC**

| Mix name | Binder | | | | | Sand (kg) | b/s | Water (kg) | w/b | SP (% of binder) |
|---|---|---|---|---|---|---|---|---|---|---|
| | CPC (kg) | GPA (kg) | TPA (kg) | F-ASH (kg) | GSP (kg) | | | | | |
| **Control** | 31.0 | - | - | - | - | 93.0 | 0.33 | 20.6 | 0.665 | - |
| **F-ASH -50** | 6.25 | - | - | 6.25 | | 37.5 | 0.33 | 6 | 0.48 | - |
| **GSP-50** | 6.25 | - | - | - | 6.25 | 37.5 | 0.33 | 6 | 0.48 | 1.5 |
| **GPA-50** | 6.25 | 9.3 | - | - | - | 37.5 | 0.33 | 6 | 0.48 | 0.6 |
| **TPA -50** | 6.25 | - | 6.25 | - | | 37.5 | 0.33 | 9.75 | 0.78 | 2 |

30% of GPA, TPA, F-ASH, and GSP by weight were used in place of the CPC with a c/s ratio of 1:3 and a w/b ratio of 0.665. The new mixes were named as F-ASH-30, GSP-30, GPA-30, TPA-30 as shown in Table 4.

**TABLE 4: Mix proportions of Control and 30% replacement of SCMs with CPC**

| Mix name | Binder | | | | | Sand (kg) | b/s | Water (kg) | w/b | SP (% of binder) |
|---|---|---|---|---|---|---|---|---|---|---|
| | CPC (kg) | GPA (kg) | TPA (kg) | F-ASH (kg) | GSP (kg) | | | | | |
| **Control** | 31.0 | - | - | - | - | 93.0 | 0.33 | 20.6 | 0.665 | - |
| **F-ASH - 30** | 21.7 | - | - | 9.3 | - | 93.0 | 0.33 | 20.6 | 0.665 | - |
| **GSP-30** | 21.7 | - | - | - | 9.3 | 93.0 | 0.33 | 20.6 | 0.665 | - |
| **GPA-30** | 21.7 | 9.3 | - | - | - | 93.0 | 0.33 | 20.6 | 0.665 | 0.4 |
| **TPA -30** | 21.7 | - | 9.3 | - | - | 93.0 | 0.33 | 20.6 | 0.665 | 1.8 |

First, the sand and binder were dry mixed for two minutes. After that, the SP mixture and around 70% of the mixing water were added, and mixed for further three minutes. After adding the remaining water, the mixing was done for five more minutes. The flow table test was then used to evaluate workability.

After that, two layers of fresh mortar were poured into steel cube molds of 50 mm in size. A vibrating table was used to condense each layer. Each cube sample was demolded a day after casting. Two accelerated curing conditions of HWC and HAC were used to cure the specimens as given in Table 5. Curing continued till the ages of 1, 7, 28, 56, 90, and 150 days for compressive strength testing.

**TABLE 5: Accelerated curing conditions**

| Number | Curing condition | Description |
|---|---|---|
| **1** | HWC | After demolding, samples were cured for the first 20 hours at 60 °C using hot water, and then at room temperature. |
| **2** | HAC | After demolding, samples were air cured at room temperature after 20 hours of hot water curing at 60 °C. |

### 2.3 Test Procedures

#### 2.3.1 Flow table test

As seen in Figure 2, a flow table test was conducted to ensure that each mortar mix had the proper workability. Two layers of mortar were poured into the semi-conical metal cylinder for this test. Ten times compressions were applied to each layer using a 16 mm steel rod. The mortar was squeezed on the flow plate once the cone was raised. The mortar and plate were then Shaked 25 times over the period of 60 seconds. The mortar was disseminated by shaking the flow table. The greatest distance between the table's two edges was noted. The mortar's flow value was determined by averaging the data collected.

**Figure. 2: Workability Assessment of Mortar Using Flow Table Test**

#### 2.3.2 Compressive Strength Measurement Test

An ELE testing apparatus with a 3000 kN capacity was used to determine the compressive strength. This high-capacity apparatus ensured accurate and consistent measurement across a wide range of mixes and strength levels. Before start of testing, the machine was calibrated according to the manufacturer's recommendations to maintain precision and to provide the relevant testing requirements. Two cube sizes, 50 × 50 × 50 $mm^3$ and 100 × 100 × 100 $mm^3$, were made for the evaluation, allowing the study to accommodate both standard testing practices with limited material availability.

The loading rate was carefully adjusted according to the dimensions of the specimens to ensure uniform stress application and to prevent premature failure. For the smaller cubes (50 mm), a pacing rate of 0.5 kN/sec was used, while for the standard 100 mm cubes, a higher rate of 2.4 kN/sec was applied. Compressive strength testing was performed at 1, 7, 28, 56, 90, and 150 days of curing to gain both early-age strength gain and long-term performance. Each specimen was properly aligned to avoid eccentric loading, and the load was applied continuously until failure.

For each mix and at each testing age, at least 3 specimens were tested, and the average of their measured compressive strengths was considered as the representative value. The results obtained were in accordance with the procedures specified in Standard (2013). This systematic approach enabled the accurate determination of strength development over time, providing a reliable basis for evaluating the mechanical performance of the studied mixes.

## 2.4 Results and discussion

### 2.4.1: Compressive Strength Test Results

Figure 3 shows the compressive strength findings for mortars Control, GPA-30, TPA-30, F-ASH-30 and GSP-30 at age ranges of 1, 7, 28, 56, 90, and 150 days under HWC curing conditions. The compressive strength of all mixes including Control, GPA-30, TPA-30, F-ASH-30, and GSP-30 generally raised with curing age. The increase in strength was determined during the age range of 1-28 days. Although strength continues to increase, the rate of strength gain tends to decrease down at older ages (beyond 28 days). At all ages, the GPA-30 continuously showed reduced compressive strength in comparison to the control mix.

In case of TPA-30, its later strength after 56, 90, and 150 days was less than the control mix, however, its early strength at 1 and 7 days was comparable to control. At the early ages of 1-7 days, F-ASH-30 exhibits noticeably reduced compressive strength. GSP-30 showed increased compressive strength at the ages of 28, 56, 90, and 150 days and approximately equivalent compressive strength to the control mix in the early stages.

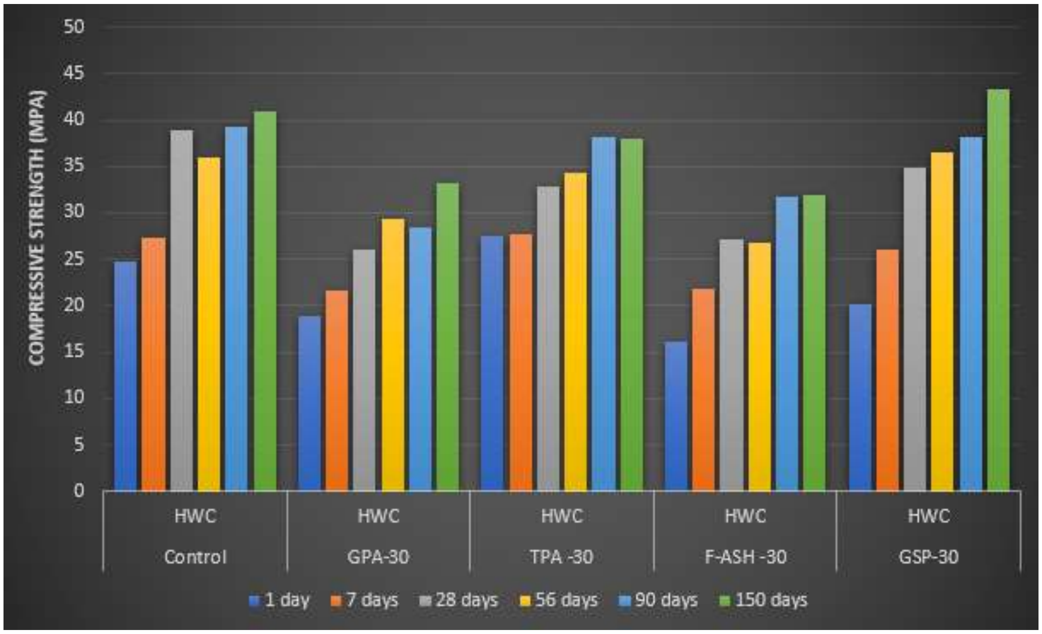


**Figure. 3: Compressive Strength of Control, GPA-30, TPA-30, F-ASH-30 and GSP-30 mortars under HWC Curing Condition**

Figure 4 shows the compressive strength results for mortars Control, GPA-30, TPA-30, F-ASH-30 and GSP-30 under HAC curing conditions at 1, 7, 28, 56, 90, and 150 days. The findings showed that overall compressive strengths of mixes were higher under HAC curing condition as compared to HWC curing conditions. The compressive strength of all mixes increased from 1 to 28 days. After 28 days, the strength development varies across different mixes. GPA-30 showed the lowest strength across all ages and gradual increases in strength over time.TPA-30 showed significant increase in strength from 1 to 28 days and the strength remained stable after 28 days. F-ASH-30 showed the lowest early strength at the age of 1 days. However, its strength increased up to 56 days. GSP-30 exhibited a consistent increase in strength up to 150 days.

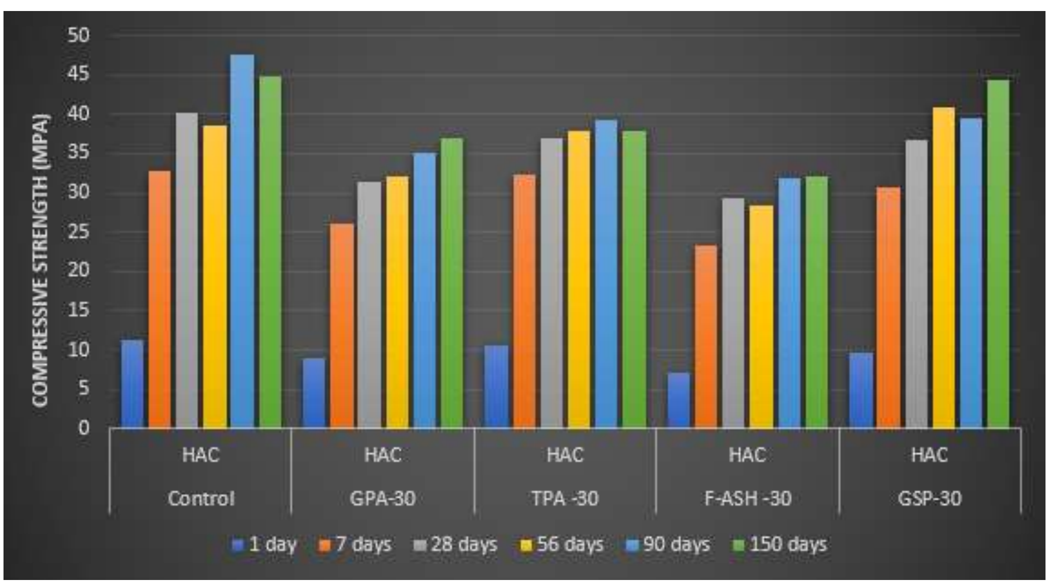


**Figure. 4: Compressive Strength of Control, GPA-30, TPA-30, F-ASH-30 and GSP-30 mortars under HAC Curing Condition**

Figure 5 shows the compressive strength findings for mortars Control, F-ASH-50, GSP-50, TPA-50, and GPA-50 under HAC curing conditions at ages of 1, 7, 28, 56, 90, and 150 days. All mixes showed an increase in compressive strength over time. The most significant strength gain occurred within the first 28 days. F-ASH-50 showed lowest strength at all ages and a gradual increase in strength over time. GSP-50 significantly gained strength throughout the testing period. It was determined that it showed highest strength at 150 days.

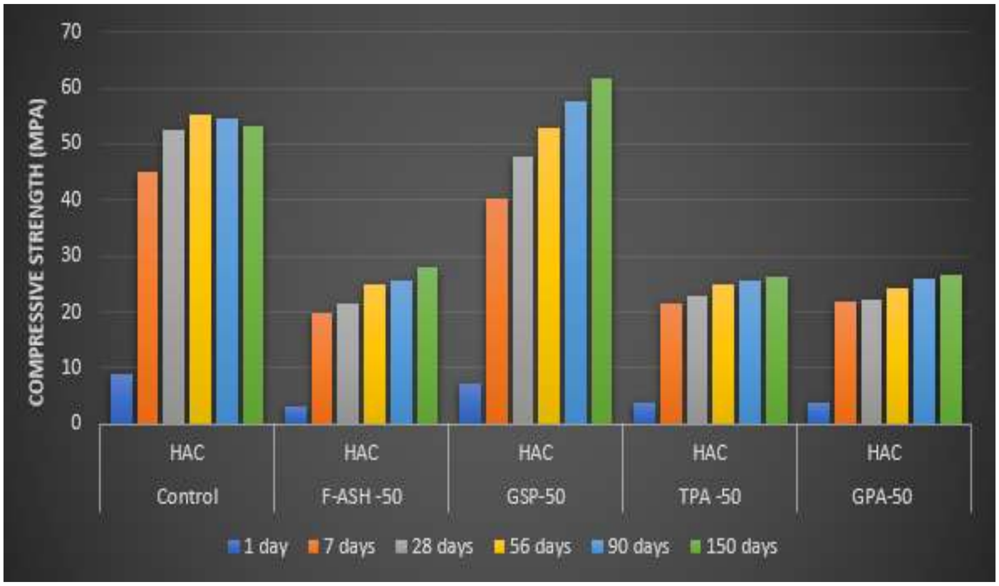


**Figure. 5: Compressive Strength of Control, F-ASH-50, GSP-50, TPA-50, and GPA-50 mortars under HAC Curing Condition**

Figure 6 shows the compressive strength values for mortars Control, F-ASH-50, GSP-50, and TPA-50 under HWC curing conditions at ages 1, 7, 28, 56, 90, and 150 days. The control mix consistently showed the highest compressive strength across all ages, starting at 29.9 MPa at 1 day and increasing to 50.1 MPa at 150 days.

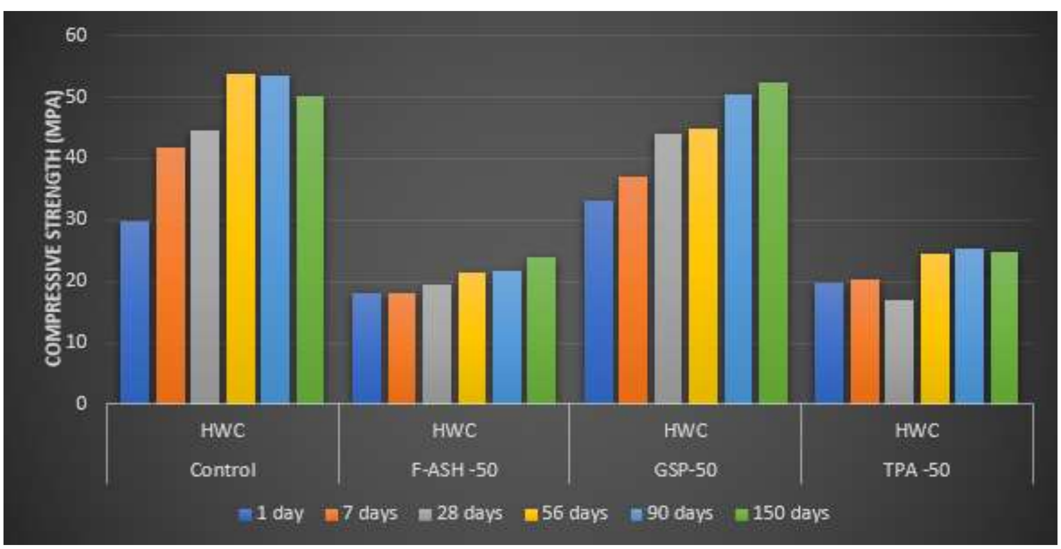


**Figure. 6: Compressive Strength of Control, F-ASH-50, GSP-50, and TPA-50 mortars Under HWC Curing Condition**

### 2.4.2: Occurrence of COE

Table 6 show the occurrence of COE in all mortars such as CPC control under HWC and HAC and blended mortars including F-ASH-30, GSP-30, GPA-30, TPA-30. The percentage losses in compressive strengths (COE %) and age of COE occurrence for all mortars is given in Table 6.

**Table 6: COE Results for all Mixes**

| Mix name | Curing condition | Age at which the crossover effect occurred (days) | Crossover effect (%) |
|---|---|---|---|
| **Control** | HWC | 56 | 7.7 |
| | HAC | 56 | 4.0 |
| | | 150 | 5.9 |
| **GPA-30** | HAC | 90 | 3.1 |
| **TPA -30** | HWC | 150 | 0.5 |
| | HAC | 150 | 3.6 |
| **F-ASH -30** | HWC | 56 | 1.8 |
| | HAC | 56 | 3.1 |
| **GSP-30** | HAC | 90 | 3.6 |

## CONCLUSIONS:

In this research using fly ash (F-ASH-30,50), granulated ballast furnace slag (GSP-30,50), ground palm oil fuel ash (GPA-30,50), and treated palm oil fuel ash (TPA-30,50) in place of conventional Portland cement, the compressive strength of mortars was measured. At 56, 90, and 150 days, it was found that the compressive strength of mortars was considerably decreased under hot air curing (HAC) and hot water curing (HWC) conditions. The outcomes are listed below.

1. Mixes having 50% replacement of supplementary cementitious materials (SCMs) such as F-ASH-50, GSP-50, GPA-50 and TPA-50, showed no COE.
2. Under HWC curing condition, F-ASH-30, GSP-30, GPA-30, TPA-30, F-ASH-50, GSP-50, GPA-50 and TPA-50 showed no COE.
3. GPA-30 under HWC showed 0.5% COE at the age of 150 days and 3.1% COE at the age of 90 days.
4. COE of 3.6% was observed in case of GSP-30 under HAC condition at the time period of 90 days.
5. F-ASH-30 showed 1.8 and 3.1 percent COE under HWC and HAC conditions at 56 days of age respectively.
6. At 150 days of age, TPA-30 produced results with COE values of 0.5 and 3.6 percent under HWC and HAC conditions, respectively.

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