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1-Year Development Trend of Concrete Compressive Strength Using Calcium Sulfoaluminate Cement Blended With OPC, PFA and GGBS

Jaime S K Yeung, Michael C H Yam, Y L Wong

Abstract

In recent years, Calcium Sulfoaluminate Cement (CSAC) has become widely used in concrete repair works due to its outstanding properties of volume stability and rapid strength gain. Nevertheless, with the increasing concerns on cost and the embodied carbon of concrete, people start considering the possibility of blended combination of CSAC with less costly Ordinary Portland Cement (OPC) and more environmental friendly binder materials like Pulverized Fuel Ash (PFA) or Ground Granulated Blasfurnance Slag (GGBS). However, due to the completely different hydration process of CSAC comparing with OPC, reactions of CSAC with these binder materials have not yet been fully understood so far through systematic research, notwithstanding that numerous studies have been done on the strength development trend of concrete with OPC blended with PFA or GGBS. The objective of this research is to determine the long-term strength development trend of concrete using different combinations of CSAC with OPC, PFA & GGBS and to derive empirical equations for predicting early and later strengths of concretes with various binder combinations incorporating CSAC at different ages. A test regime consisting of totally 20 concrete mixes was conducted to examine the effect of different binder combinations on the concrete *compressive strength at different ages from 2 hours up to one year (365 days). The test results show that with the same total binder content, concrete mixes with increasing percentage content of CSAC exhibit increasing early strength. For concrete mixes with combination of CSAC with PFA or GGBS only, their concrete compressive strengths at later ages drop significantly when OPC is not present. This is believed to be the result of lacking of calcium hydroxide, which is the hydration product of OPC, to activate the hydraulic properties of PFA or GGBS to contribute in strength development. Nevertheless, it is found that a small quantity down to 5% of OPC is already adequate to bring the long-term strength at 365 days up to the same order as that of ordinary pure OPC concrete. Equations are derived for the prediction of strength performance of concrete with various binder combinations at different ages for the consideration of engineers at design or planning stage. Outcome of this research is able to give a picture for the strength development trends of concretes with different percentage combinations of CSAC with commonly used binder materials. The derived equations also give valuable information at the design stage for engineers to determine suitable percentage of different binder materials in concrete to be used giving a balance of benefits in the aspects of strength performance at early and long-term stages as well as economic and environmental considerations.*

Key Words: Calcium Sulfoaluminate Cement (CSAC); Ordinary Portland Cement (OPC); Pulverized Fuel Ash (PFA); Ground Granulated Blasfurnace Slag (GGBS); Binder materials;

Early ettringite formation; Strength Development Trend

1. Introduction

Concrete using Calcium Sulfoaluminate Cement (CSAC) has an outstanding volume stability and rapid strength development at early stage [1, 2, 3, 4] and is therefore often used in concrete with requirement of achieving substantial early strength in a few hours' time. However, concretes with pure CSAC may not be necessary in cases where very high early strength (e.g. 20 MPa or above at 2 hours). Hence, binder combinations with OPC, PFA or GGBS are often considered instead of pure CSAC mix to cater for lower carbon footprint and lower cost. CSAC, PFA and GGBS are commonly used binder replacement materials bearing much lower carbon footprint, less heat of hydration and further strength growth at later stage with their hydraulic properties in the secondary hydration reaction with OPC [5,6,7,10,11]. However, since the chemical reaction of the hydration process of CSAC and the resulted hydration product are in fact different from those of OPC [12, 13], the performance of hydraulic properties of PFA and GGBS, when they are blended with CSAC, is not fully understood. Although numerous studies have been carried out in the past to examine the strength development trend of concrete with OPC blended with PFA or GGBS and other benefits of the inclusion of PFA or GGBS in concrete, little systematic research has been conducted so far on the long term (up to the period of one year) development trend of compressive strength for concrete with the blended combination of CSAC and other binder materials [4,5,6,7,10,11,12,13,14]. Lukas et al [21] found that addition (not replacement) of 5 to 15% by mass of PFA to CSAC concrete mix gave an increase in compressive strength by up to 3 – 6 MPa after 28 days but higher addition rate of PFA in turn had adverse effect of a reduction in compressive strength but the chemical reaction involved was still not firmly identified. Due to lack of reliable reference for strength development trend of concrete with pure CSAC or CSAC blended with other binder materials, numerous trials are often required for the determination of the most suitable binder combination not only for the early strength performance but also the 28-day and ultimate strength. The early strength performance of the intended mix proportion can be obtained quickly by laboratory tests at the planning stage but the latter two properties, which are more important concerns for concrete, require more time for verification. Based on the test results collected in this study, empirical equations are established for the predictions of the strength characteristics of concrete mixes at early age at 2 – 6 hours as well as later ages at 28 days and 365 days, which is taken as the ultimate strength, with various binder combinations to ease concrete mix design with cost estimation and carbon footprint calculation at the planning stage. With the knowledge of the long-term strength development performance and a prediction of the anticipated strength at early and later ages of the concrete, misuse or reservation about the use of CSAC in combination with other binder material(s) can be avoided. The objective of this study is to investigate the strength development trend of concrete using different combinations of OPC, PFA and GGBS with CSAC at different ages including that (1) early ages in 2 – 6 hours, (2) 28 days and (3) 365 days and to derive empirical equations for the prediction of early and later strengths of concretes with various binder combinations incorporating CSAC at different ages.

The derived equations can be used by engineers at the design and planning stage for projects using concrete with designated binder content incorporating CSAC.

2. Materials and Test Programme

Based on the information provided by the manufacturer, the CSAC used in this study contains 80% of CSAC clinker and 20% of anhydrous calcium sulfate while the clinker contains 58% of Yeelimite and 12% of Belite. OPC, PFA and GGBS employed in this study are the materials commonly available in Hong Kong market and their key ingredients are summarized in Table 1.

Twenty concrete mixes with different binder combinations were tested in this experimental programme. CSAC used in this study was manufactured by CTS Cement Corporation and complying to GB/T 20472: 2006. The OPC used is Class 52.5N Type CEM1 conforming to BS EN 197-1: 2000. The PFA (also known as fly ash) and GGBS used in this study are sourced from the Hong Kong market and conform to BS EN 450-1: 2012 and BS EN 15167-1: 2006 respectively. The coarse and fine aggregates used are from the same source from Mainland China and conform to BS EN 12620: 2013. All the 20 concrete mixes with different binder combinations conducted in this study as shown in Table 2 were controlled with the same total binder content of 420 kg, the water to binder ratio of 0.42 and the maximum aggregate size of 20 mm. A polycarboxylic based water reducing agent (product name of SP8S ex BASF) with the dosage of 1.2% by weight of binder content and a set stabilizing admixture (product name of Delvocrete ex BASF) with the dosage of 1 liter per cubic meter of concrete (for concrete mixes with CSAC only) are used in the concrete mixes for achieving the target slump of 150 mm and the workable time of at least 45 minutes for operation. For each concrete mix, 20 numbers of 100mm cube specimens (2 for each age) were cast for testing compressive strength at ages of 2 hours, 4 hours, 6 hours, 1 day, 7 days, 14 days, 28 days, 90 days, 180 days and 365 days. Mix Identifications (Mix IDs) are assigned to each concrete mix based on the percentage contents of each binder material included in the format of (% of CSAC) / (% of OPC) / (% of PFA) / (% of GGBS). For instance, the Mix ID of 37.5/37.5/25/0 represents the concrete mix composing of 37.5% of CSAC, 37.5% of OPC, 25% of PFA and 0% of GGBS. The cube specimens were tested in accordance with Hong Kong Construction Standard 1 Section 12: "Determination of compressive strength of concrete cubes", which is basically the same as BS EN 12390-3: 2009 "Compressive Strength of Test Specimens" except that the curing temperature is 27^{o}C ± 2^{o}C for the age of 2, 4 & 6 hours, 1 day, 7 days, 14 days, 28 days, 90 days, 180 days and 365 days. Compressive strength results were then compared in groups of similar combination of binder materials for the investigation of strength development trend of each combination.

3. DISCUSSION ON TEST RESULTS

3.1 Summary of test results and indications

Compressive strength test results at ages from 2 hours up to 365 days of all concrete mixes involved in this study are summarized in Table 3 showing different strength development trends of concrete mixes with different binder combinations. Compressive strength test results for the 20 concrete mixes involved in this study were grouped by the binder combinations of CSAC/OPC, CSAC/OPC/PFA and CSAC/OPC/GGBS for analysis to determine the difference in performance with different binder combinations and the contribution in strength development of each binder material in each combination. Test results at different ages for each group of binder combinations are plotted in graphs as illustrated in Figs 1 to 3. The development trends of the compressive strength for the 20 concrete mixes from early ages of 2 hours up to 365 days of the 20 concrete mixes are discussed separately by groups of different combinations of binder materials (CSAC/OPC, CSAC/OPC/PFA & CSAC/OPC/GGBS) with respect to their different attributes in the hydration processes.

For CSAC/OPC blended mixes (100/0/0/0, 75/25/0/0, 50/50/0/0 & 25/75/0/0), early strengths at ages from 2 hours to 1 day increase with increasing % of CSAC content. Strength performance of concretes with less % of CSAC but more OPC slowly picked up afterward and reached similar level as those of concretes having much higher early strength. This demonstrates that OPC and CSAC have similar ultimate strength gain ability and their coexistence in the same concrete mix do not materially affect each other's hydraulic properties.

For CSA/OPC/PFA blended mixes, the early strength performance is in direct proportion to the % of CSAC. However, strength performance at both early and ultimate ages (365 days) for CSAC/PFA blended mixes (Mixes 75/0/25/0, 65/0/35/0 & 55/0/45/0) drop with decreasing % of CSAC although the % of PFA increases simultaneously. This indicates that PFA has little or even adverse effect in strength gain in this binder combination and the trend agrees with what has been found by Lukas et al [21] although the contents of yeelimite and belite in the CSACs used in the two studies are different. It can be explained that PFA requires calcium hydroxide, which is the hydration product of OPC but not CSAC [3,6,9,12], to activate its pozzolanic reactivity for strength gain. When OPC is included in the binder content (Mixes 37.5/37.5/35/0, 32.5/32.5/35/0 27.5/27.5/45/0, 70/5/25/0 & 65/10/25/0), their 28-day strengths increase significantly when comparing to the CSAC/PFA mixes and the increments are directly proportional to the % of OPC. All these concrete mixes achieve the same strength levels of pure CSAC mix (100/0/0/0) and pure OPC mix (0/100/0/0) after 90 days up to 365 days depending on the % of OPC consisted in the binder content. As evidenced by the strength at 365 days for the mix with only 5% of OPC (70/5/25/0) (64.4

MPa) and compare it with that of the pure OPC mix (0/100/0/0) (67.1 MPa), it proves that the hydraulic reaction of PFA for strength gain requires only little percentage of OPC. The strength gain process is much slower although additional effect of PFA in the hydrated mix such as nucleation, reaction of amorphous alumina, etc. may have also given their contribution. Further studies for the hydraulic reaction of PFA with small quantities of OPC in long term strength development may also be an interested topic for other researchers. From the strength development trends of mixes 37.5/37.5/35/0, 32.5/32.5/35/0 27.5/27.5/45/0, 65/10/25/0 & 70/5/25/0, it further verifies that the higher the OPC content in the CSAC/OPC/PFA blended mixes, the earlier will the strength performance catch up with that of pure OPC (0/100/0/0) or pure CSAC (100/0/0/0) mixes.

For CSAC/OPC/GGBS blended mixes, the early strength performance is again in direct proportion to the % of CSAC similar to that of CSAC/OPC/PFA blended mixes. By comparing the CSAC/PFA and CSAC/GGBS blended mixes with the same proportion of the two binders (Mixes 65/0/35/0 & 65/0/0/35), the latter has higher strength performance from 7 days up to 365 days. Comparing with PFA, GGBS has proved its stronger hydraulic ability [5,7] for strength gain without the presence of OPC and the two CSAC/GGBS mixes (65/0/35/0 & 65/0/035) are even able to attain the same ultimate strength level at 365 days as that of the two CSAC/OPC/GGBS mixes (32.5/32.5/0/35 & 17.5/17.5/0/65) although the pace of strength gain of the two CSAC/GGBS mixes is relatively slower than that of the two

CSAC/OPC/GGBS mixes, which hydration process are accelerated by the hydration product (calcium hydroxide) of OPC [5,7]. It is also noticed that the early strength performance at 2 to 6 hours of the CSAC/GGBS blended mix (65/0/0/35) seems to have retarded when comparing with the CSAC/PFA blended mix (65/0/35/0) with the same CSAC content. It is recommendation to explore the reason for this in future studies.

3.2 Prediction of Early Strength Performance for Combinations of the Four Binders:

Early strength results for concrete mixes with CSAC are shown in Table 3. All concrete mixes containing CSAC show decreasing early strength performance with decreasing percentage of CSAC in the total binder content. Hydration of OPC for strength development only takes place after its final stiffening time, which is normally several hours after addition of water. Moreover, majority of the strength contribution of PFA and GGBS requires activation of the hydration product of OPC [5,6,10,11,12]. In this regard, OPC, PFA and GGBS can be considered not to have any contribution in early strength development in a few hours' time. The early strength performance of CSAC depends on the composition of its clinker and % of calcium sulphate added. On the other hand, concrete mixes containing less than 25% of CSAC also do not show measurable early strength performance. As such, based on the early strength test results obtained in this study for concrete mixes with various CSAC content, it can be concluded that when a concrete mix is required to exhibit early strength property within 6 hours, at least 25% of CSAC in the total binder content should be used in the mix design. To investigate the pattern of early strength development of concrete incorporating at least 25% of CSAC, early strength results of 2, 4 and 6 hours for these concrete mixes are listed in Table 4. The average early strengths at 2, 4 and 6 hours of the concrete mixes in Table 4 are presented as percentages (Y) to that of the 100% CSAC mix. These percentages (Y) are then plotted against their respective % of CSAC (X) as shown in Figure 4. A linear relationship is obtained and the correlation equation is derived from the graph with a coefficient of determination of 0.97.

$Y = 1.1703X - 0.2385$, which is then simplified to $Y = 1.17X - 0.24$

The following equation is then derived for the prediction of early strength performance of a concrete mix containing at least 25% of CSAC:

$$\mathbf{S_{CSACe} = S_{CSACe\text{-}100}\,(1.17P_{CSAC} - 0.24)} \qquad \textbf{(Eq. 1)}$$

Where:

$S_{CSACe\text{-}100}$ is the early strength of a concrete with 100% CSAC in the binder content at an early age between 2 to 6 hours;

P_{CSAC} is the percentage of CSAC in the binder content of a new concrete mix;

S_{CSACe} is the early strength of the new concrete mix at the same age of the concrete mix with 100% CSAC ($S_{CSAe\text{-}100}$).

3.3 Prediction of 28-day and ultimate Compressive strength performance for Combinations of the Four Binders:

28-day and ultimate (represented by the 365-day result in this study) compressive strengths are the most concerned mechanical property of concrete in structural design while the 28-day compressive strength is normally set as the prime compliance criterion for concrete quality. The following notations are used for establishing equations to forecast the 28-day and ultimate compressive strength performance of concrete with CSAC blended with other binder materials.

$S_{CSAC/OPC/X\text{-}AGE}$ = Compressive strength of a CSAC/OPC/X blended mix where X represent either PFA or GGBS, while OPC may or may not exist. "AGE" can be put as 28 days or 365 days.

$S_{OPC\text{-}AGE}$ = Compressive strength of the pure OPC mix at the same "AGE".

$SF_{X\text{-}AGE}$ = Strength factor of the binder X, which is the contribution in strength at "AGE" of the binder X of a concrete mix with respect to that of a pure OPC mix, which is taken as 1.00.

P_X = Percentage of the binder X in the total binder content in a concrete mix

From the test results in this study, concretes with CSAC blended with other binder materials perform differently in terms of compressive strength at 28 days. Unlike the study for early strength development, the strength performance at 28 days of pure OPC mix is more commonly known and is therefore used as the reference mix for predicting the 28-day strength of concretes with other binder combinations. Nominal strength factor for 28-day strength (SF_{X-28}) of each binder material X is defined as the ratio of its contribution in 28-day strength to that of the same percentage content of OPC, for which the nominal strength factor (SF_{OPC-28}) is taken as 1.0.

With these terms defined, equations can be derived from the test results of concrete mixes in each group of the same binder combination by considering the contribution in strength of each of the binder and its own strength factor with respect to that of OPC at the same age while concretes containing PFA or GGBS are dealt with separately.

For binder combinations of CSAC/OPC/PFA and CSAC/OPC/GGBS, the strength development at 28 days can be derived from the following mathematical statement (MS 1).

$$\mathbf{S_{CSAC/OPC/PFA-28}=(S_{OPC-28})[(SF_{CSAC-28})(P_{CSAC})+(SF_{OPC-28})(P_{OPC})+(SF_{PFA/GGBS-28})(P_{PFA/GGBS})]}$$

This equation can be used to find out the strength factors of each binder material with respect to the strength contribution of the content of OPC in each binder combination at the specified age. The strength factors can then be used to project the strength of a concrete mix with various percentages of binder materials at specified ages.

When putting the 28-day strength results (55.8 MPa, 56.5 MPa, 57.2 MPa & 58.4 MPa) of the pure CSAC mix (100/0/0/0) and CSA/OPC blended mixes (75/25/0/0, 50/50/0/0 and 25/75/0/0) into the mathematical statement (MS 1) for the comparison with the pure OPC mix (0/100/0/0), the strength factor of CSAC (SF_{CSA-28}) are calculated to be 0.95, 0.95, 0.95 and 0.98 respectively with the average of 0.95. The nominal strength factor of CSAC ($SF_{CSAC-28}$)

is therefore taken as 0.95.

From the 28-day strength results in Table 3, concrete mixes containing PFA perform quite differently when OPC is present or absent. In the hydration process of OPC, calcium hydroxide (CH) is generated which increases the alkalinity of the pore water in the concrete matrix to activate the pozzolanic reaction of PFA [6]. In CSAC/PFA blended mixes, since the hydration process of CSAC does not produce calcium hydroxide [1,2,3], it is expected that the pozzolanic reactivity of PFA cannot be activated with the absence of OPC. Not only that, as evidenced by the 28-day strength of CSAC/PFA blended mixes (75/0/25/0, 65/0/35/0, 55/0/45/0), PFA even gives a reduction in 28-day strength. Their 28-day strength results show a descending trend with the reduction in CSAC content, which is compensated by the increment of PFA in the same percentage. By putting the nominal strength factor of CSAC ($SF_{CSA\text{-}28}$) of 0.95 in the evaluation of the 28-day strength results of these three CSAC/PFA blended mixes, the strength factors of PFA ($SF_{PFA\text{-}28}$) calculated from the mathematical statement (MS 1) are -0.36, -0.42 and -0.28 respectively. The average of the three results (-0.36) is taken as the nominal strength factor ($SF_{PFA\text{-}28}$) for PFA with absence of OPC.

In CSAC/OPC/PFA blended mixes, calcium hydroxide (CH) generated in the hydration process of OPC activates the pozzolanic reaction of PFA [6] resulting in a positive contribution for 28-day strength. However, for mixes 70/5/25/0 and 65/10/25/0, their 28-day strengths are still lagging behind other mixes with the same binder combination

(CSAC/OPC/PFA). It is believed that the CH concentration in the binder matrix is too low due to the presence of small percentage of OPC, and thus lead to slow pace of the secondary hydration of PFA. In this regard, results of concrete mixes with little percentage of OPC are not taken into account for the calculation of the strength factor of PFA with presence of OPC. The slow pace of secondary hydration of PFA in low concentration of CH is proved to continue up to the ultimate stage (365 days) in subsequent discussion. 28-day strength results for CSAC/OPC/PFA and OPC/PFA blended mixes of 37.5/37.5/25/0, 32.5/32.5/35/0 and 27.5/27.5/45/0 are put into the mathematical statement (MS 1) with the adoption of $SF_{CSAC-28}$ and SF_{OPC-28} as 0.95 and 1.0 respectively. The strength factors of PFA calculated from mixes 37.5/37.5/25/0, 32.5/32.5/35/0 and 27.5/27.5/45/0 are 0.41, 0.33 & 0.33 respectively. Their average, which is calculated to be a positive value of 0.36, is then taken as the nominal strength factor for PFA with presence of OPC, SF_{PFA-28}.

Similar to CSAC/PFA mixes, the compressive strengths of the concrete cubes at 28 days with CSAC/GGBS blended mixes (65/0/0/35 and 35/0/0/65) are substantially lower than those of pure CSAC and pure OPC mixes. This is due to the absence of secondary hydration of GGBS without the presence of OPC. Nevertheless, unlike PFA, GGBS still has contribution in 28-day strength by the hydration effect of its own [5,6,7,10,11]. By putting the nominal strength factor of CSAC ($SF_{CSAC-28}$ = 0.95) and 28-day strength results of the two mixes of 65/0/0/35 and 35/0/0/65 into the mathematical statement (MS 1), the average of the two calculated strength factors (0.27 & 0.32) is 0.30, which is then taken as the nominal strength factor for GGBS with absence of OPC ($SF_{GGBS-28}$).

Similarly, the 28-day strength results of mixes 32.5/32.5/0/35 and 17.5/17.5/0/65 and the nominal strength factors of CSAC (0.95) and OPC (1.0) are put into the mathematical statement (MS 1). The nominal strength factor for GGBS in the presence of OPC ($SF_{GGBS-28}$) is then calculated to be 0.60 from the average of the results (0.68 & 0.52) obtained in this equation. Since OPC activates the secondary hydration of GGBS with its hydration product of CH, the nominal strength factor of GGBS in the presence of OPC is higher than that of GGBS without OPC indicating the positive effect of OPC for the strength development of concrete incorporating GGBS.

From the derivation above, the nominal strength factors for PFA and GGBS with and without the presence of OPC at 28-day in the concrete mix are therefore determined to be SF_{PFA-28} = -0.36 and 0.36; $SF_{GGBS-28}$ = 0.30 and 0.60 with and without presence of OPC respectively.

These nominal strength factors are put into the mathematical statement (MS 1). By putting in the determined strength factors at 28 days of all the ingredients and providing that PFA and GGBS does not coexist in the binder combination, the equation for predicting 28-day strengths of CSAC/OPC/PFA and CSAC/OPC/GGBS blended concrete become:

$$\mathbf{S_{CSAC-28}=(S_{OPC-28})[0.95(P_{CSAC})+(P_{OPC})+SF_{PFA/GGBS-28}(P_{PFA/GGBS})]} \qquad \textbf{(Eq. 2)}$$

Where: the strength factors SF_{PFA-28} is -0.36 (with OPC) or 0.36 (without OPC), and

$SF_{GGBS-28}$ is 0.30 (with OPC) or 0.60 (without OPC).

The estimated 28-day strengths of the respective concrete mixes are summarized in Table 5 and plotted against the actual 28-day strengths of corresponding concrete mixes obtained in this study as shown in Figure 5. The relationship between the estimated strength and the actual strength is found to be linear with the coefficient of determination (R^2) of 0.9806. This indicates that 28-day strength performance can be predicted accurately with Equation 2 for concrete mixes containing CSAC blended with other binder materials. It is well-known that strength development of concrete still continues after the age of 28 days, especially those containing supplementary binder materials like PFA or GGBS, but the development trend will be largely dependent on the combination of binder materials, which perform differently after the age of 28 days due to different mechanisms of their hydration processes [5,6,7,10,11,14]. Notwithstanding that the 28-day compressive strength is normally the compliance criteria for concrete quality, engineers also have concern with the ultimate strength development of concrete, which contributes to enhancing the safety factor in structural design and to a certain extent, also have indication for the concrete durability. Although it has been proved by some previous researches that strength of concrete may continue to develop up to the age of 30 years when stored under moist condition [18], the increment in strength up the age of 365 days has already reached almost the apex barring some exceptional cases. In this regard, the 365-day compressive strength of concrete is taken as its ultimate compressive strength in this study.

From the test results given in Table 3, all the mixes with different percentage combinations of CSAC and OPC do not show significant difference in their ultimate strength at 365 days although the strength development trends at intermediate ages between 7 to 365 days are different. Similar to the performance at 28 days, pure CSAC has similar, although a bit lower, 365-day strength than that of pure OPC concrete. The 365-day compressive strengths of concrete mixes 100/0/0/0 (65.8 MPa), 75/25/0/0 (58.9 MPa), 50/50/0/0 (62.1 MPa) and 25/75/0/0 (68.6 MPa) with CSAC/OPC combinations are very close to each other and are also similar to that of the pure OPC mix 0/100/0/0 (67.7 MPa). In this regard, it seems that CSAC and OPC do not affect each other's ultimate strength when they are combined together. With similar approach to the calculation of strength factor of each binder material for 28-day strength, mathematical statement can also be derived from the 365-day test results of concrete mixes in each group of the same binder combination by considering the contribution in strength of each of the binder and its own strength factor with respect to that of OPC at the same age.

For binder combinations of CSAC/OPC/PFA and CSAC/OPC/GGBS, the strength development at 365 days can be derived from the following mathematical statement (MS 2).

$S_{CSAC/OPC/GGBS\text{-}365}=(S_{OPC\text{-}365})[(SF_{CSAC\text{-}365})(P_{CSAC})+(P_{OPC})+(SF_{PFA/GGBS\text{-}365})(P_{PFA/GGBS})]$

By putting the 365-day strength results of mixes 100/0/0/0, 75/25/0/0, 50/50/0/0 and

25/75/0/0 into mathematical statement (MS 2), the strength factors for CSAC at 365 days ($SF_{CSAC-365}$) in these mixes are calculated to be 0.97, 0.83, 0.83 and 1.05 respectively. Their average (0.92) is taken as the nominal strength factor of CSAC at 365 days.

From the 365-day compressive strength results for concrete mixes 75/0/25/0, 65/0/35/0 and 55/0/45/0, it can be observed that an increase in PFA content together with a reduction in CSAC content in the CSACC/PFA blended mixes show significantly strength reduction at 365 days (41.7 MPa, 32.3 MPa & 25.8 MPa respectively). Again, these results show that PFA does not only have no contribution in strength development with the absence of OPC, it even gives detrimental effect on the strength development when blended with CSAC alone. This phenomenon is in line with the performance of CSAC/PFA blended mix at the age of 28 days as mentioned earlier and also agrees with the findings by Lukas et al [21] although their previous research was only up to the age of 90 days. By substituting the 365-day strength of the three concrete mixes 75/0/25/0, 65/0/35/0 and 55/0/45/0 in the mathematical statement (MS 2), the strength factors for PFA in the absence of OPC are calculated to be -0.30, -0.34 & -0.31. Their average (-0.32) is then taken as the nominal strength factor for PFA at 365 days with CSAC in the absence of OPC ($SF_{PFA-365}$), which is found to be the same as the nominal strength factor for PFA at 28-day.

With the presence of OPC in the binder combination, its hydration product of calcium hydroxide reacts with PFA as the secondary hydration process and contributes to strength development [6]. For Mix 70/5/25/0 and Mix 65/10/25, there are only 5% and 10% OPC and thus the calcium hydroxide generated from the hydration process of OPC is relatively little. This leads to slower pozzolanic reaction of PFA in the concrete mix for strength development. Notwithstanding this, the compressive strength of Mix 70/5/25/0 and Mix 65/10/25 can still catch up with other mixes of pure OPC and OPC/PFA blends at the age of 365 days. This proves that PFA does not actually require much OPC for activating the secondary hydration but the pace of strength development is dependent on the concentration of calcium hydroxide generated by the OPC present. Similarly, the compressive strengths of concrete mixes of 37.5/37.5/25/0, 32.5/32.5/35/0, 27.5/27.5/45/0, 70/5/25 and 65/10/25/0 (67.1 MPa, 64.1 MPa, 64.0 MPa, 64.4 MPa and 65.5 MPa respectively) are substituted in mathematical statement (MS 2). The results of strength factor for PFA obtained are 1.04, 0.89, 0.91, 0.95 and 1.00 with the average of 0.95, which is then taken as the nominal strength factor for PFA with the presence of OPC.

Unlike the distinct performance of PFA in concrete mixes with or without the presence of OPC, GGBS shows similar contribution in strength development up to 365 days in both conditions of binder combinations. By substituting the 365-day strength results of CSAC/GGBS and CSAC/OPC/GGBS blended concrete mixes of 65/0/0/35 (59.3 MPa), Mix 35/0/0/65 (57.2 MPa), Mix 32.5/32.5/0/35 (60.3 MPa) and Mix 17.5/17.5/0/65 (58.4 MPa) in mathematical statement (MS 2), the results obtained for the strength factor of GGBS

($SF_{GGBS-365}$) are 0.74, 0.79, 0.73 and 0.8. Their average of 0.77 is then taken as the nominal strength factor of GGBS at 365 days irrespective of the presence of OPC.

Similar to what has been done for predicting the 28-day strength of concrete mixes with different binder blends, an equation is also proposed to calculate the equivalent OPC content in concrete mixes with any combination of the four binder materials (CSAC, OPC, PFA & GGBS) in terms of the performance in ultimate strength at the age of 365 days.

By putting in the determined strength factors at 365 days of all the ingredients and providing PFA and GGBS does not coexist in the binder combination, the equation for CSAC/OPC/PFA and CSAC/OPC/GGBS blended concrete become:

$$\mathbf{S_{CSAC\text{-}365}=(S_{OPC\text{-}365})[0.95(P_{CSAC})+(P_{OPC})+SF_{PFA/GGBS\text{-}365}(P_{PFA/GGBS})]} \qquad \textbf{(Eq. 3)}$$

Where: the strength factors $SF_{PFA-365}$ is -0.36 (with OPC) or 0.95 (without OPC), and $SF_{GGBS-365}$ is 0.77 (with or without OPC)

With this Equation 3, the estimated 365-day strengths of the respective concrete mixes are calculated as shown in Table 6 and are used to plot against the actual 365-day strengths of corresponding concrete mixes in Figure 6. The coefficient of determination (R^2) of 0.9672 confirms that predictions made will be rather accurate.

3.4 Applicability of the equations for predicting compressive strength performance

Different forms of Ye'elimite, which is also known as Klein's compound, and different percentages of calcium sulphate in CSAC among various manufacturing sources of different cement plants may give different results in early strength performance. Having said that, ingredients of the CSAC used in this study is within the common range for other CSAC available in the market. In addition, the total binder content of 450 kg/m^3 of concrete and the water to binder ratio of 0.42 are also commonly adopted parameters in concrete mix designs, the early strength prediction derived in this study can therefore be used for reference in most applications. Moreover, the equations developed in this study is for the prediction of strength performance of concrete at later ages with CSAC as the key binder in combination of other binder material(s) based on the known strength of an OPC concrete mix with the same binder content and water to binder ratio at the same age. In this regard, the equations should also apply to concrete mixes with other binder contents and water to binder ratios while verification of such can also be included in next stage of the study. The PFA content of 25% - 45% and GGBS content of 35% - 65% are the most commonly used proportions in concrete mixes using these two supplementary binders. The equations should therefore apply to most concrete mixes commonly used in the industry. Nevertheless, it should be noted that the development trends of concrete with different binder combinations may vary between the age of 28 days and 365 days for different binder combinations and these equations cannot be used for predicting compressive strengths at other ages.

4. Conclusions

Based on the above findings, the following conclusions can be drawn from this study:

(a) Concrete with pure CSAC exhibits very good early strength in two to six hours and is also able to achieve similar strength level as those of pure OPC, OPC/PFA and OPC/GGBS concrete mixes at 28 days and later ages up to 365 days.

(b) For concretes with CSAC incorporated with other binder materials, equations are developed to predict compressive strength at ages of 2 – 6 hours, 28 days and 365 days with Equations 1, 2 and 3 respectively.

(c) Without the presence of OPC, PFA exhibits a detrimental effect on the strength development up to the ages of 28 days and 365 days when blended with CSAC alone. The reason for the reduction in strength at later ages by PFA in CSAC/PFA blended mixes is unknown. Further study is recommended to determine the reason for the detrimental effect of PFA in strength development in CSAC/PFA blended mix.

(d) At the age up to 365 days, little quantities of OPC (5% in Mix 70/5/25/0) contained in mixes incorporating PFA is already adequate to fully utilize its hydraulic properties. Nevertheless, the smaller the quantity of OPC present, the slower is the strength development pace.

(e) In the absence of OPC, GGBS exhibits its own contribution in strength development when blended with CSAC comparing with the detrimental effect of PFA under the same condition.

(f) When OPC is present, contribution of GGBS in strength development is larger than that of PFA up to the age of 28 days. However, when the age is increased to 365 days, PFA has larger contribution in strength than GGBS even when there is only little quantity of OPC present.

5. Acknowledgement

This study included laboratory mixing trials of a total of 20 concrete mixes with 400 standard cubes for compression tests at 10 different ages from 2 hours up to 365 days. The mixing trials as well of all the standard cubes were prepared and tested by the laboratory technicians of Multi-Way Industries Limited. The authors would like to express their heartfelt appreciation to their selfless dedication to this research study.

Appendix: Tables and Figures:

Table 1: Materials used in the study

Material	**Main Ingredients**					
CSAC	Clinker: 82%			Addition: 18%		
	Yeelimite	Belite	Others	Anhydrous Calcium Sulfate		
	58%	12%	12%	18%		
Other Binders	CaO	Al2O3	MgO	Fe2O3	SiO2	Others
OPC	65	6	2	4	20	4
PFA	2	30	2	8	48	10
GGBS	40	12	8	0.5	35	5

Table 2: Mix designs used in the study:

Mix No.	Mix Identification	Binders (in kg)			
		CSAC	OPC	PFA	GGBS
1	100/0/0/0	420	0	0	0
2	75/25/0/0	315	105	0	0
3	50/50/0/0	210	210	0	0
4	25/75/0/0	105	315	0	0
5	75/0/25/0	315	0	105	0
6	65/0/35/0	273	0	147	0
7	55/0/45/0	231	0	189	0
8	0/100/0/0	0	420	0	0
9	37.5/37.5/25/0	158	157	105	0
10	32.5/32.5/35/0	137	136	147	0
11	27.5/27.5/45/0	116	115	189	0
12	0/75/25/0	0	315	105	0
13	0/65/35/0	0	273	147	0
14	5/95/0/0	21	399	0	0
15	70/5/25/0	294	21	105	0
16	65/10/25/0	273	42	105	0
17	65/0/0/35	273	0	0	147
18	35/0/0/65	147	0	0	273
19	32.5/32.5/0/35	136	137	0	147
20	17.5/17.5/0/65	74	73	0	273

Note to Table 1:

(a) The percentages of PFA and GGBS adopted in this study are the most commonly used in Hong Kong.

(b) Delvocrete Stabilizer (manufacturer: BASF) is used to regulate the workable time of concrete mixes having CSAC.

Table 3: Compressive Strength Results at Different Ages

Mix Identification	**2 hrs**	**4 hrs**	**6 hrs**	**1 day**	**7 days**	**14 days**	**28 days**	**90 days**	**180 days**	**365 days**
	Compressive Strength in MPa									
100/0/0/0	25.7	29.2	34.7	40.1	46.3	53.5	55.6	57.8	65.4	65.8
75/25/0/0	16.3	18.7	21.5	27.3	36.2	40.7	54.5	55.0	58.4	58.9
50/50/0/0	8.6	10.4	12.6	16.4	37.4	45.7	57.0	62.1	62.1	62.1
25/75/0/0	4.5	6.7	8.0	9.4	44.8	48.5	58.6	68.6	68.6	68.6
75/0/25/0	16.9	20.6	22.8	25.6	33.5	33.6	36.5	37.1	39.0	41.7
65/0/35/0	16.5	18.1	20.7	22.8	24.6	26.3	27.0	28.8	29.4	32.3
55/0/45/0	10.2	13.4	16.3	18.3	21.1	21.4	23.3	25.0	25.2	25.8
0/100/0/0	--	--	--	19.2	51.5	56.9	58.7	64.7	64.2	67.7
37.5/37.5/25/0	4.8	5.1	7.2	8.8	24.2	37.0	48.9	61.2	65.1	67.1
32.5/32.5/35/0	3.3	4.1	5.2	6.0	18.6	31.2	44.0	62.1	63.9	64.1
27.5/27.5/45/0	2.1	2.5	3.8	4.7	13.1	25.9	39.8	55.8	62.0	64.0
0/75/25/0	--	--	--	14.4	31.7	38.1	48.3	53.8	61.8	63.3
0/65/35/0	--	--	--	10.8	25.7	33.6	44.5	51.1	64.2	62.5
5/95/0/0	--	--	--	20.1	46.0	50.9	55.9	60.6	64.1	66.0
70/5/25/0	9.8	11.9	12.7	15.5	16.3	16.9	37.4	46.2	50.5	64.4
65/10/25/0	9.2	10.6	11.4	14.5	15.8	15.8	39.1	50.4	61.3	65.5
65/0/0/35	--	13.0	16.3	23.2	31.6	31.6	41.8	48.9	56.7	59.3
35/0/0/65	--	4.4	4.9	6.9	12.7	21.0	31.7	41.6	49.3	57.2
32.5/32.5/0/35	--	3.8	5.4	10.9	38.3	47.6	51.3	56.0	58.1	60.3
17.5/17.5/0/65	--	--	--	3.5	22.4	30.5	40.1	52.2	54.1	58.4

Note to Table 3:
"--" denotes that there was not enough strength of the concrete for demoulding.

Table 4: Early strength results and their % to that of CSAC concrete

Mix ID	**% of CSAC**	**Early strength results (MPa)**			**Average %**	**% of early strength to that of 100% CSAC concrete**
		2 hrs.	4 hrs.	6 hrs.		
100/0/0/0	100%	25.7	29.2	34.7	29.9	100%
75/25/0/0	75%	16.3	18.7	21.5	18.8	63%
50/50/0/0	50%	8.6	10.4	12.6	10.5	35%
25/75/0/0	25%	4.5	6.7	8.0	6.4	21%
75/0/25/0	75%	16.9	20.6	22.8	20.1	67%
65/0/35/0	65%	16.5	18.1	20.7	18.4	62%
55/0/45/0	55%	10.2	13.4	16.3	13.3	45%
37.5/37.5/25/0	37.5%	4.8	5.1	7.2	5.7	19%
32.5/32.5/35/0	32.5%	3.3	4.1	5.2	4.2	14%
27.5/27.5/45/0	27.5%	2.1	2.5	3.8	2.8	9%
70/5/25/0	70%	9.8	11.9	12.7	11.5	38%
65/10/25/0	65%	9.2	10.5	11.4	10.4	35%
65/0/0/35	65%	10.1	12.1	14.8	12.3	41%
35/0/0/65	35%	3.5	4.4	4.9	4.3	14%
32.5/32.5/0/35	32.5%	2.7	3.8	4.8	3.8	13%

Table 5: Actual tested 28-day strength Vs Estimated 28-day strength based on Strength Factors of Various Binder Materials

Mix IDs	Percentage of Binder Content and Their Strength Factors at 28-day of: $SF_{CSAC-28}$=0.95; SF_{OPC-28}=1.00; SF_{PFA-28}= - 0.36, (without OPC); SF_{PFA-28}=0.36 (with OPC); $SF_{GGBS-28}$=0.3 (without OPC); $SF_{GGBS-28}$=0.6 (with OPC)				Combined Strength Factor w.r.t compressive strength of Pure OPC concrete at 28-day (SCF)	Estimated 28-day strength Of pure OPC mix (0/100/0/0) X SCF	Actual 28-day strength results (MPa)
	P_{CSAC}	P_{OPC}	P_{PFA}	P_{GGBS}			
100/0/0/0	100%	0%	0%	0%	95.0%	55.8	55.6
75/25/0/0	75%	25%	0%	0%	96.3%	56.5	57.0
50/50/0/0	50%	50%	0%	0%	97.5%	57.2	54.5
25/75/0/0	25%	75%	0%	0%	98.8%	58.0	58.6
75/0/25/0	75%	0%	25%	0%	62.3%	36.5	36.5
65/0/35/0	65%	0%	35%	0%	49.2%	28.9	27.0
55/0/45/0	55%	0%	45%	0%	36.1%	21.2	23.3
0/100/0/0	0%	100%	0%	0%	100.0%	58.7	58.7
37.5/37.5/25/0	37.5%	37.5%	25%	0%	81.9%	48.1	48.9
32.5/32.5/35/0	32.5%	32.5%	35%	0%	75.6%	44.4	44.0
27.5/27.5/45/0	27.5%	27.5%	45%	0%	69.4%	40.7	39.8

0/75/25/0	0%	75%	25%	0%	83.8%	49.2	48.3
0/65/35/0	0%	65%	35%	0%	77.3%	45.3	44.5
5/95/0/0	5%	95%	0%	0%	99.8%	58.6	55.9
70/5/25/0	70%	5%	25%	0%	N/A	N/A	37.4
65/10/25/0	65%	10%	25%	0%	N/A	N/A	39.1
65/0/0/35	65%	0%	0%	35%	71.9%	42.2	38.4
35/0/0/65	35%	0%	0%	65%	52.1%	30.6	30.7
32.5/32.5/0/35	32.5%	32.5%	0%	35%	84.4%	49.5	54.3
17.5/17.5/0/65	17.5%	17.5%	0%	65%	73.1%	42.9	39.1

Table 6: Actual tested 365-day strength Vs Estimated 365-day strength based on Strength Factors of Various Binder Materials

Mix IDs	**Percentage of Binder Content and Their Strength Factors at 365-day of: $SF_{CSAC-28}$=0.95; SF_{OPC-28}=1.00; SF_{PFA-28}= - 0.36, (without OPC); SF_{PFA-28}=0.95 (with OPC); $SF_{GGBS-28}$=0.77**				**Combined Strength Factor w.r.t compressive strength of Pure OPC concrete at 365-day (SCF)**	**Estimated 365-day strength Of pure OPC mix (0/100/0/0) X SCF**	**Actual 365-day strength results (MPa)**
	P_{CSAC}	**P_{OPC}**	**P_{PFA}**	**P_{GGBS}**			
100/0/0/0	100%	0%	0%	0%	95.0%	64.3	64.8
75/25/0/0	75%	25%	0%	0%	96.3%	65.2	64.5
50/50/0/0	50%	50%	0%	0%	97.5%	66.0	65.5
25/75/0/0	25%	75%	0%	0%	98.8%	66.9	66.6
75/0/25/0	75%	0%	25%	0%	62.3%	42.1	41.7
65/0/35/0	65%	0%	35%	0%	49.2%	33.3	33.3
55/0/45/0	55%	0%	45%	0%	36.1%	24.4	25.6
0/100/0/0	0%	100%	0%	0%	100.0%	67.7	67.7
37.5/37.5/25/0	37.5%	37.5%	25%	0%	96.9%	65.6	67.1
32.5/32.5/35/0	32.5%	32.5%	35%	0%	96.6%	65.4	64.1
27.5/27.5/45/0	27.5%	27.5%	45%	0%	96.4%	65.2	64.0

0/75/25/0	0%	75%	25%	0%	99.8%	67.5	63.3
0/65/35/0	0%	65%	35%	0%	95.3%	64.5	62.5
5/95/0/0	5%	95%	0%	0%	95.5%	64.7	66.0
70/5/25/0	70%	5%	25%	0%	88.7%	60.0	64.4
65/10/25/0	65%	10%	25%	0%	83.3%	56.4	65.5
65/0/0/35	65%	0%	0%	35%	90.3%	61.2	59.3
35/0/0/65	35%	0%	0%	65%	84.2%	57.0	57.2
32.5/32.5/0/35	32.5%	32.5%	0%	35%	95.0%	64.3	60.3
17.5/17.5/0/65	17.5%	17.5%	0%	65%	96.3%	65.2	58.4

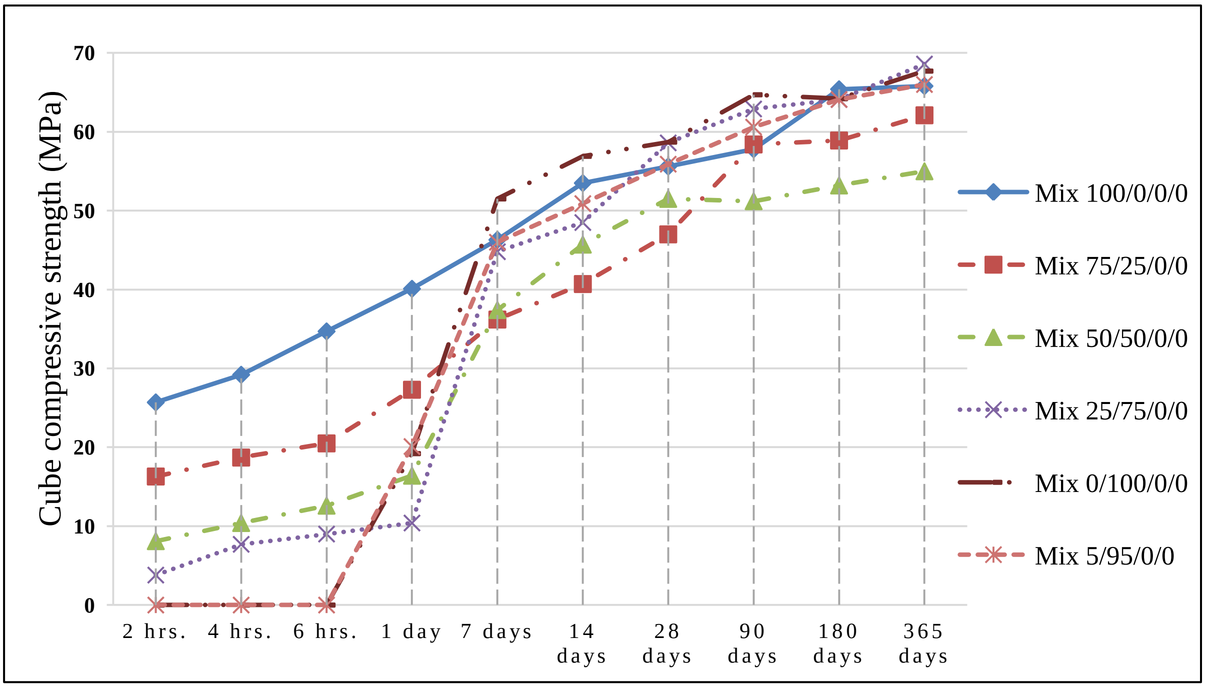

Figure 1: Strength Development Trend of CSA/OPC Concretes

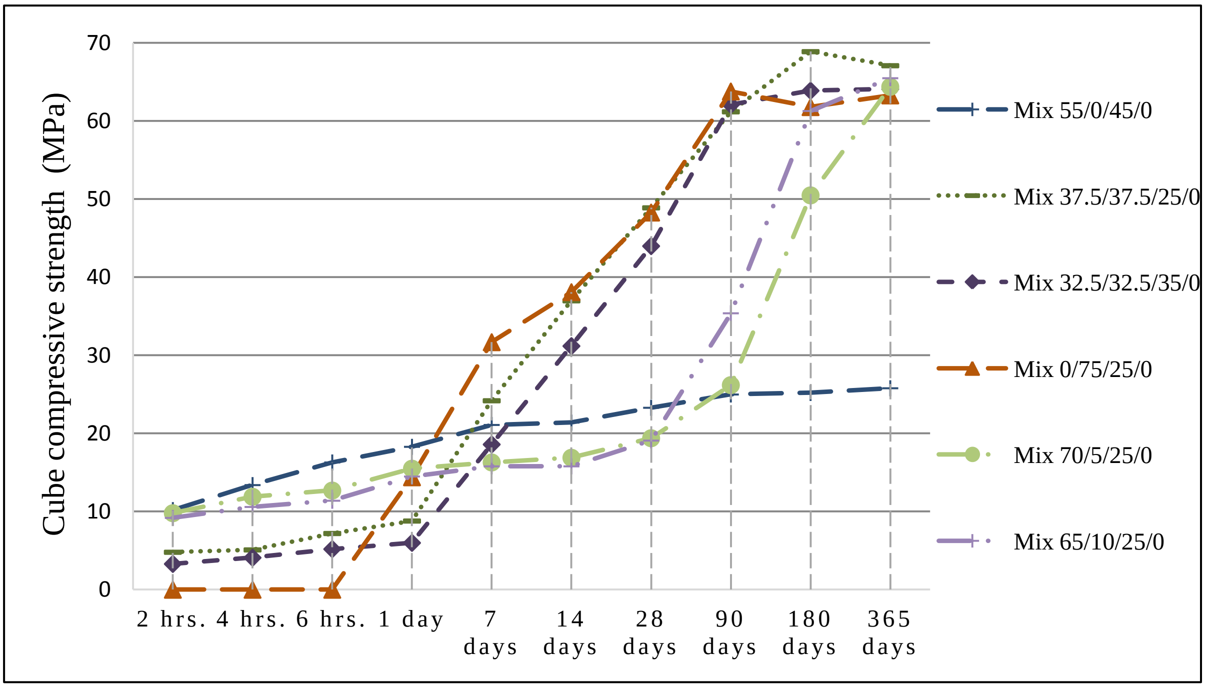

Figure 2: Strength Development Trend of CSA/OPC/PFA Concretes

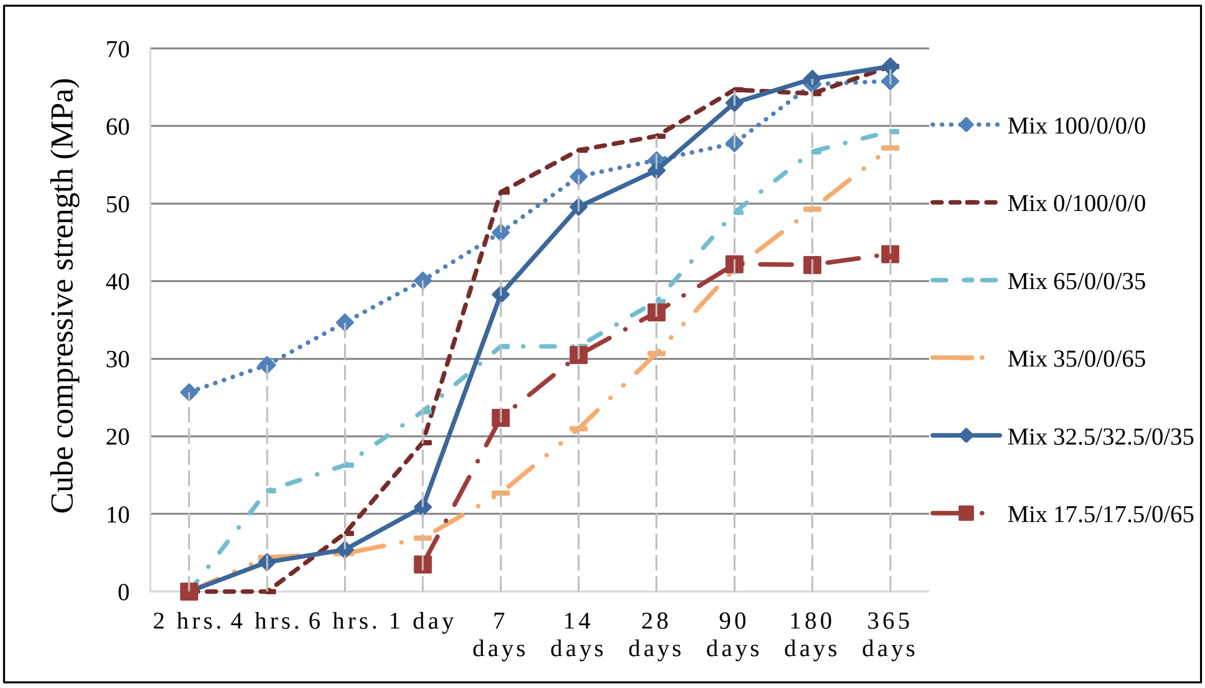

Figure 3: Strength Development Trend of CSA/OPC/GGBS Concretes

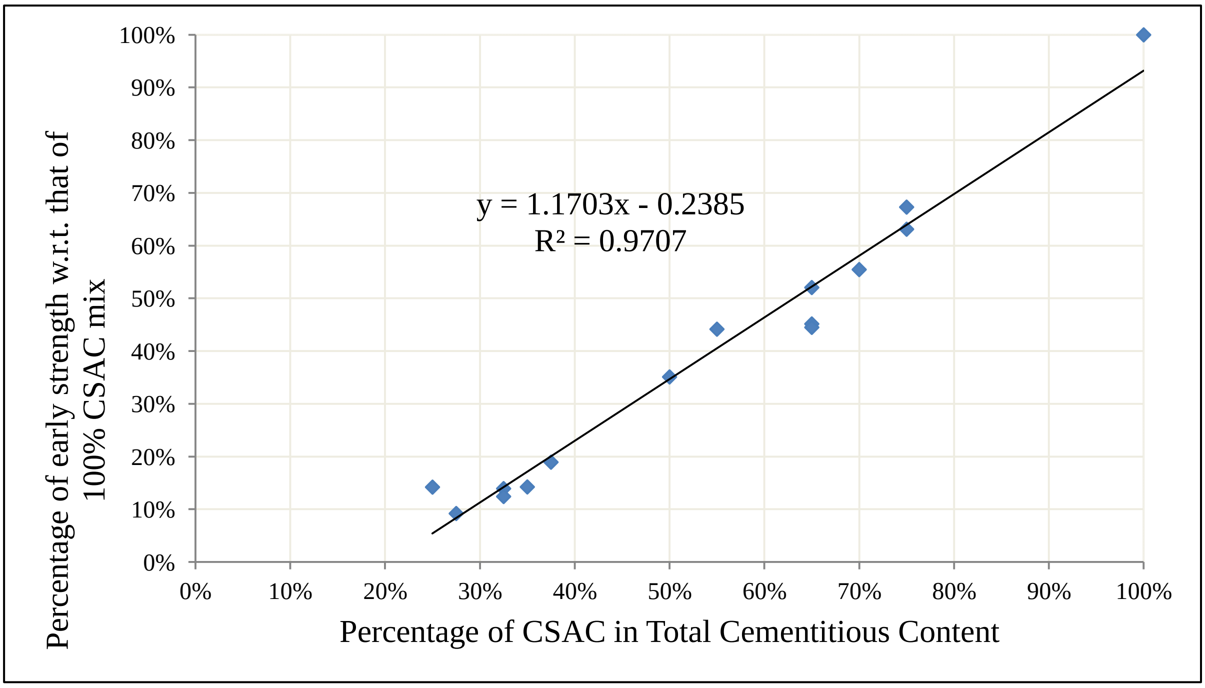

Figure 4: Relationship between the % of CSAC in total binder content and the % of early strength performance w.r.t. that of 100% CSAC concrete

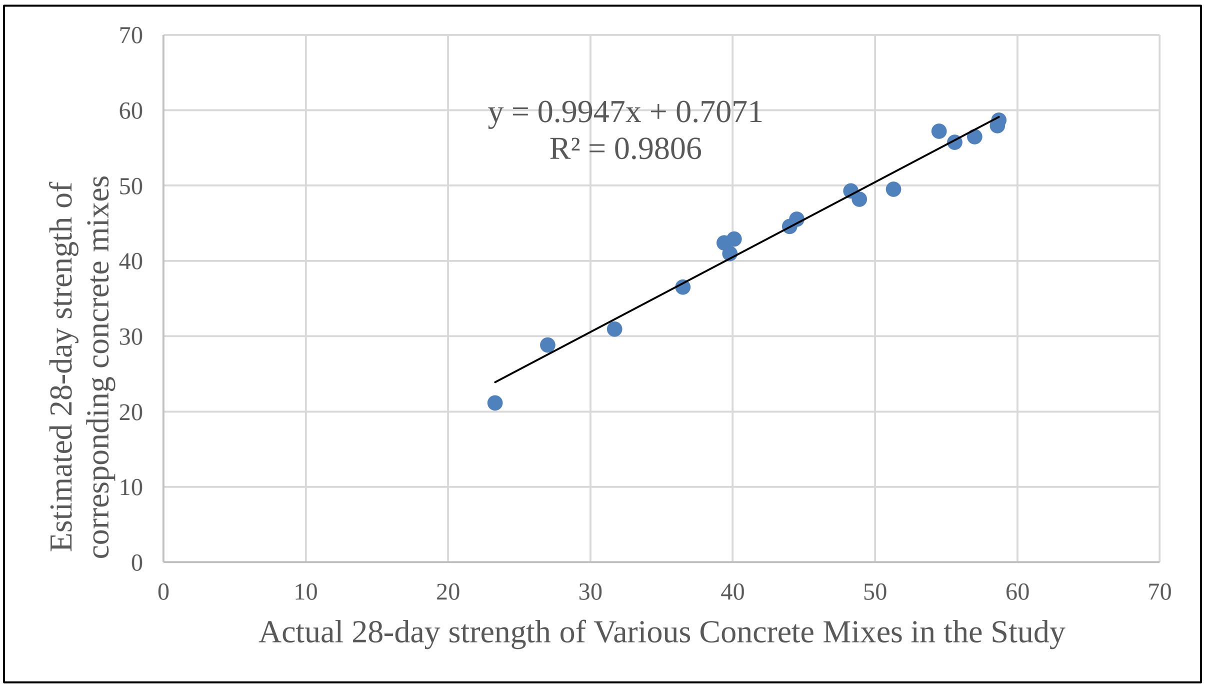

Figure 5: Actual 28-day strength Vs Estimated 28-day strength by equation using nominal strength factors of binders

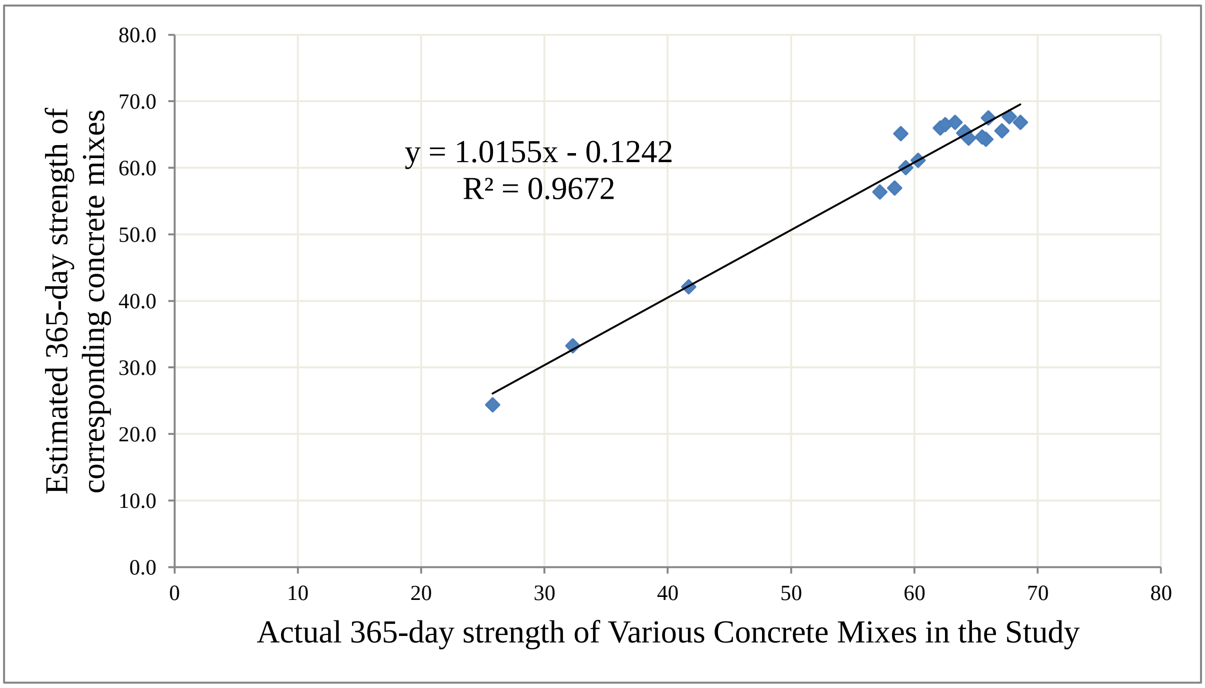

Figure 6: Actual 365-day strength Vs Estimated 28-day strength by equation using nominal strength factors of binders

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