A STUDY OF THE EFFECT OF CALCIUM SULFOALUMINATE CEMENT ON THE STRUCTURAL PROPERTIES OF CONCRETE

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A Study of the Effect of Calcium Sulfoaluminate Cement on the Structural Properties of Concrete

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CERTIFICATE OF ORIGINALITY

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Abstract

This research study is to explore the effect of Calcium Sulfoaluminate Cement (CSAC) on the structural properties of concrete when being used as the key binder in combinations with Ordinary Portland cement (OPC), Pulverized Fuel Ash (PFA) and Ground Granulated Blastfurnace Cement (GGBS).

Following the increasing use of CSAC in structural concrete applications utilizing its characteristics in early strength and/or low shrinkage, there are needs for obtaining more knowledge of its structural properties in comparison with conventional concretes incorporating OPC, PFA and GGBS only. Structural properties of CSAC concretes studied in this research are the development trends of compressive strength (from a few hours to 1 year) and shrinkage (from early to ultimate stage) as well as its fire resistance performance represented by strength reduction after exposure to elevated temperature.

Experimental approach was adopted to obtain test results from a total of 20 concrete mixes were studied for analysis, based on which conclusions are made for the development trends of CSAC concretes in strength and shrinkage up to the age of one year. Reduction in strength at 28 days after exposure to an elevated temperature of 300^{o}C are also collected for comparison with those given in current design codes.

Based on predicting models developed in previous literatures for conventional concretes using OPC as the key binder, new models for predicting the strength development of CSAC concretes of various binder combinations with OPC, PFA and GGBS are established for enabling engineers to easily estimate the strength performance of such concretes while long period trial tests are often impractical.

Similarly, prediction models for shrinkage of concretes using OPC are currently available in well-recognized literatures but not covering concretes incorporating CSAC in binder combination. By using the test results obtained in this study, correction factors for various binder materials other than OPC are derived for putting in the widely adopted GL2000 Model given in ACI 209.2R-08: “Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete”. With the newly derived correction factors, the applicability of the GL2000 Model is broadened to cover concretes with various binder combinations of CSAC, OPC, PFA and GGBS.

Strength reduction factors after exposure to elevated temperature of 300°C for concretes incorporating CSAC were also obtained in the study for evaluating the fire resistance of concretes incorporating CSAC.

Lastly, rapid strength development and volume stability characteristic of pure CSAC concrete at early ages and its ability to achieve similar long-term strength as that of pure OPC concrete are confirmed. Effects of combining CSAC with PFA and GGBS in terms of development of strength and shrinkage as well as the fire resistance represented by reduction in strength after exposure to elevated temperature were concluded. Based on the study results, limitations of applicability of results obtained in this study and the use of CSAC concrete in structural applications are given. Further studies on more properties of CSAC concrete in comparison with conventional OPC concrete incorporating commonly used supplementary binder materials of PFA and GGBS are suggested.

List of publications

A. Journal papers that have been published

1. **J. S. K. Yeung**, M. C. H. Yam, Y. L. Wong, *'1-Year development trend of concrete compressive strength using calcium sulfoaluminate cement blended with OPC, PFA and GGBS'*, Construction and Building Materials, 198 (2019), 527–536.

2. **J. S. K. Yeung**, M. C. H. Yam, Y. L. Wong, *'Model for predicting shrinkage of concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS'*, Journal of Building Engineering, 32 (2020), p. 101671.

B. Journal papers that are under preparation

1. **J. S. K. Yeung**, M. C. H. Yam, Y. L. Wong, *'Fire-resistant properties of concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS'*

2. **J. S. K. Yeung**, M. C. H. Yam, Y. L. Wong, *'Elastic deformation in terms of Young's modulus for concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS'*

C. Conference papers that have been presented

1 J. S. K. Yeung, *'Incorporation of Calcium Sulfoaluminate cement in concrete and the resulted properties'*, Nano and Advanced Materials Institute Annual Conference October 2013.

2 J. S. K. Yeung, "Environmental Friendly Applications of Calcium Sulfoaluminate Cement and Its Characteristics in Combinations with Other Binder Materials" (硫鋁酸鹽水泥的環保應用及其它膠凝材料混合的特性', 兩岸四地工程師研討會) 2012.

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List of Symbols and Abbreviations

CSAC	calcium sulfoaluminate cement
ε_{shu}	ultimate shrinkage strain
ε_{sh-365}	shrinkage strain at 365 days
ε_{28}	shrinkage strain at 28 days
ε_{t}	shrinkage strain at time t
ε_{tc}	corrected shrinkage strain at time t
f	shrinkage factor of test specimen given in ACI 209.02R-08
h	hour(s)
GGBS	ground granulated blast-furnace slag
OPC	ordinary Portland cement
PFA	pulverised fuel ash
K_{B}	K factor for binder B in GL2000 model
K_{BC}	combined K factor for concretes with various binder combinations
K_{CSAC}	K factor for CSAC binder alone in GL2000 model
$K_{CSAC/GGBS}$	combined K factor for CSAC/GGBS binder mix in GL2000 model
$K_{CSAC/OPC}$	combined K factor for CSAC/OPC binder mix in GL2000 model
$K_{CSAC/PFA}$	combined K factor for CSAC/PFA binder mix in GL2000 model
$K_{CSAC-OPC}$	K factor for CSAC in GL2000 Model in presence of the % of OPC adopted in this study
$K_{CSAC/OPC/GGBS}$	combined K factor for CSAC/OPC/GGBS binder mix in GL2000 model
$K_{CSAC/OPC/PFA}$	combined K factor for CSAC/OPC/PFA binder mix in GL2000 model
K_{OPC}	K factor for OPC binder in GL2000 model
$K_{OPC/PFA}$	combined K factor for OPC/PFA binder mix in GL2000 model
K_{PFA}	K factor for PFA binder alone in GL2000 model

$K_{PFA-OPC}$	K factor for PFA in GL2000 Model in presence of the % of OPC adopted in this study
K_{GGBS}	K factor for GGBS binder alone in GL2000 model
$K_{GGBS-OPC}$	K factor for GGBS in GL2000 Model in presence of the % of OPC adopted in this study
P_X	percentage of a binder X (CSAC, OPC, PFA or GGBS) in binder combination in a concrete
S	surface area of test specimen for shrinkage measurement
S_{CSACe}	early strength (at 2–6-h) of concrete containing ≥25% CSAC
$S_{CSACe-100}$	early strength (at 2–6-h) of concrete containing 100% CSAC
S_{X-AGE}	strength of concrete containing the binder material combination X (e.g., CSAC, OPC, CSAC/OPC, OPC/PFA, CSAC/OPC/PFA or CSAC/OPC/GGBS) at the age of AGE (e.g., 28 or 365 days)
SF_{X-AGE}	strength factor of a binder material (e.g., CSAC, OPC, CSAC/OPC, OPC/PFA, CSAC/OPC/PFA or CSAC/OPC/GGBS) at the age of AGE (e.g., 28 or 365 days)
SRF_X	strength reduction factor derived in this study for concrete containing CSAC and exposed to elevated temperature X°C
SRF_{S-X}	strength reduction factor given in current design code for OPC concrete exposed to elevated temperature X°C
t	time (days) since the end of moist curing
V	volume of test specimen for shrinkage measurement
V/S	volume/surface area ratio for test specimen
$\%_B$	percentage of binder material B in concrete mix

Chapter 1 Introduction

1.1 Research background and current research gaps

Ordinary Portland cement (OPC), pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS) are the most common materials used as binders in concrete [1]. In recent years, there has been growing demand in construction projects, alterations and additions works and concrete repair applications for concretes that contain belitic type of calcium sulfoaluminate cement (CSAC) as a binder because of their rapid strength gains and excellent volumetric stability, which are superior to those of concretes containing the conventional binders mentioned above [2, 3, 4]. There are typical examples of the application of CSAC in concretes for structural applications in Hong Kong including (i) concretes for footings, columns and bridge deck of a footbridge at a rocky beach requiring high early strength to resist tidal force; (ii) reinstatement works for damaged carriageway on trunk roads with busy traffic where only 6 hours of traffic closure can be allowed for the works; and (iii) recasting of cantilever slab outside tenants' units at a public housing estate that requiring high early concrete strength for early removal of temporary props and early re-opening of the area for the affected tenants. Based on these job examples, using CSAC in concrete is beneficial for early attainment of compressive strength meeting the required structural performance. The early strength development of CSAC concretes results from the early formation of ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$) and the heat generated at the early hydration stage, which, in turn, accelerates the hydration reaction and has been explored [5–7]. However, the relatively high cost of CSAC compared to OPC, and the lack of information on its long-term performance parameters, which are required in structural concrete design, has limited its use. As shown in previous studies [8–11], PFA and GGBS are environmentally friendly supplementary binders that can be blended with OPC to form cheaper and greener concretes that generate less heat and have a lower carbon footprint than pure OPC concretes, provided that the 28-day compressive strength and long-term strength performance of PFA or GGBS-containing concretes are regulated in the mix design to be similar to those of pure OPC.

In real-life applications where early strength is only required for light-duty work (i.e., work involving forces of a few MPa), a concrete binder content of 100% CSAC is not necessary. In such cases, the use of OPC, PFA or GGBS in the binder matrix has both cost and environmental benefits, provided that, as mentioned above, the resulting concretes have properties similar to those of pure OPC concretes. However, the hydration process and subsequent hydration product of CSAC in concrete are distinct from those of OPC. Consequently, understanding about the interactions between CSAC and other binders in concretes is little, compared with the known effects of OPC binder in conventional concretes. Moreover, it is well known that the contributions of PFA and GGBS binders to concrete strength and their roles in shrinkage mechanisms are highly dependent on their reactions with calcium hydroxide ($Ca(OH)_2$), the hydration product of OPC [8–11]. However, although the interactions between OPC, PFA and GGBS in the hydration process are understood [8–11], there has been little research on the interactions of CSAC with other binders in binder blends and the resulting effects on key concrete quality parameters, such as mechanical strength and shrinkage. Engineers are thus not confident in using concretes containing CSAC as a binder, or blends of CSAC and other binders, as it is impossible to estimate at the design stage the long-term strength and shrinkage performance of such concretes. Consequently, as the demand for concretes containing multiple binder materials (including CSAC) is growing continuously due to their cost and environmental benefits, it is crucial that reliable models for predicting the long-term strength performance and shrinkage of such concretes are established.

Design codes stipulate that structural engineers must have an understanding of a concrete used for structural applications [12–14], such that they can assess its strength performance at critical stages of application. The strength of early-age concrete determines its ability to withstand the planned loading, the time required for formwork striking or the suitability of re-opening a structure for service during repair works, among other aspects. Aside from the early strength of concrete, its strength at the age of 28 days is a critical parameter, as it determines the ability of the concrete to achieve the characteristic strength required in structural design. The prediction of ultimate shrinkage is also crucial in the structural design of a concrete structure, as it allows for crack-control measures and possible deflections due to stripping and reshoring [15]. Structural engineers may consult predictive models given in the literature [15–18] to estimate the ultimate shrinkage and compressive strengths of different ages of concrete. However, the existing predictive models used to generate these estimates are based on concretes that contain OPC as the key binder. For example, in the ACI 209.2R-08 ("Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete") [15], the predictive models are explicitly stated to be applicable to concretes that contain OPCs of types I (normal), II (moderately sulphate-resistant) and III (high early strength), as classified in ASTM C150-07 ("Standard Specification for Portland Cement") [19]. As binder composition is the main factor that determines the properties of concretes examined in this study, the direct application of these predictive models for OPC concretes to predicting the properties of CSAC concretes is unwise. In this regard, there is a need for appropriate predictive models for CSAC concretes that would enable structural engineers to predict the compressive strength and shrinkage of these concretes at the design stage.

In addition to suitable physical and mechanical properties, concretes for structural applications must be sufficiently resistant to a loss of structural integrity when exposed to elevated temperature conditions during fires. This means that reductions in the strength of structural concrete at elevated temperatures, and the associated risk of spalling, must be taken into account in structural design. Fire-resistant characteristics are given in current design codes [12–14], together with measures to mitigate the risk of spalling in high-strength concrete (grade C80 or higher) and strength reduction factors for concretes exposed to different elevated temperature levels, with respect to 28-day compressive strengths under normal curing. Nevertheless, these strength reduction factors also were originally established for concretes containing a binder comprising OPC alone or in combination with PFA and GGBS.

A well-known property of CSAC is its early formation of ettringite crystals during hydration. This leads to rapid strength gains in early-age concretes, in addition to expansion of the ettringite crystal to compensate for shrinkage, leading to volumetric stability. However, the stability of ettringite crystals under elevated temperatures has not been well studied, and possible decreases in concrete strength after exposure to elevated temperatures are not stated in current design codes [12–14]. Thus, as ettringite crystals are the main contributors to the strength of concretes with CSAC binder matrices, it is doubtful that their stabilities or their reductions in strength after exposure to elevated temperatures (e.g., 300°C) are similar to those given in current design codes [12–14] for concretes containing ordinary binder materials (OPC, PFA and GGBS) that are used for interior structures. The applicability of the strength reduction factors given in current design codes to concretes incorporating CSAC binder is therefore uncertain.

In the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14], strength reduction factors ranging from 1 to 0 are given for concrete exposed to temperatures from 20°C to 1200°C, which implies that a concrete will lose all of its strength when exposed to a temperature approaching 1200°C. For example [14], when the exposure temperature is approximately 300°C, the given strength reduction factor is 0.85, which equates to an estimated strength decrease of approximately 15%. Thus, to determine the fire-resistant properties of concretes that do and do not incorporate CSAC binder, the strength reduction factors at 300°C for concrete mixes containing different binder combinations are calculated from the test results that were obtained in this study. The relationship between the CSAC content of the binder of a concrete and the resulting fire resistance of the concrete are also established in terms of changes in its strength reduction factor after exposure to the same temperature level.

Overall, there are three significant aspects to this research. First, the strength development trends of concretes containing CSAC binder, alone or in combination with other binders, were experimentally determined. From these data, equations for predicting the compressive strength of concrete at critical ages (i.e., a few hours, 28 days and 365 days) are derived to enable the optimal estimation of the expected strength performance of concretes containing various combinations of CSAC, OPC, PFA and GGBS binders, although the co-use of PFA and GGBS is not yet allowed in local design code and specifications. This will allow the compressive strength of a concrete with the same binder content and water-to-binder ratio as those used in this study to be estimated at critical ages by simply inputting the percentages of each binder present in the binder combination into the equations.

Second, the GL2000 model given in ACI 209.2R-08 (“Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete”) [15] is used, but different correction factors (K factors) are developed for CSAC, PFA and GGBS binders, as only OPC has been previously examined using the GL2000 model. These newly developed K factors broaden the applicability of the GL2000 model, such that it can be used to predict the ultimate shrinkage strain of concretes that contain various combinations of CSAC, OPC PFA and GGBS binders, rather than being limited to predicting these properties in concretes containing only OPC (types I, II or III cement), as classified in ASTM C150-07 (“Standard Specification for Portland Cement”) [19].

Third, although concretes containing CSAC as a binder have already adopted in some structural applications in Hong Kong, their fire resistance has not been studied in terms of their reduction in strength after exposure to elevated temperatures. This represents a knowledge gap in the use of CSAC binder, in particular for building works that require concretes to have fire-resistant properties. The strength reduction factors obtained in this study for concretes incorporating CSAC in their binder combinations are therefore compared with those given in the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14]. Then, the relationship between the CSAC content in binder combinations of concretes and the change in the strength reduction factor of these concretes when exposed to a certain elevated temperature are established. This enables the fire-resistant properties at an elevated temperature of 300°C (a medium fire-exposure condition) to be determined for a concrete containing CSAC as a binder and compared with those of ordinary concrete containing OPC as a key binder.

1.2 Objectives and scope

The aim of this study was to examine and evaluate the performance of concretes containing CSAC binder blended in different percentage combinations with OPC, PFA and GGBS binders in terms of the compressive strength, shrinkage and fire resistance.

The research objectives of this study were:

(a) To experimentally examine the compressive strength development trends of concretes containing CSAC binder, and also various combinations of CSAC, OPC, PFA and GGBS binders, up to the age of 365 days, and to study the roles of each binder and their contributions to these properties;

(b) To derive predictive equations to estimate the compressive strength at critical ages of concretes containing CSAC binder;

(c) To experimentally investigate the shrinkage performance of concretes containing CSAC binder or various combinations of CSAC, OPC, PFA and GGBS binders, and the influence of each binder on this performance;

(d) To establish appropriate correction factors for different binders for use in the GL2000 model to predict the ultimate shrinkage strains of concretes containing various binder combinations;

(e) To compare the fire resistance capabilities of concretes containing CSAC binder with the strength reduction factors given in current design codes; and

(f) To identify the limits of applicability of concretes containing CSAC binder.

1.3 Organisation of this thesis:

This thesis is composed of eight chapters.

Chapter 1 introduces the research background and the current knowledge gap. The increasing popularity of CSAC as a concrete binder in various applications is discussed. In addition, the high early strength and volumetric stability advantages of concrete containing CSAC binder are explained. This chapter also highlights the growing demand for concretes containing CSAC blended with other commonly used binders, such as OPC, PFA and GGBS, to realise environmental and cost benefits. Finally, the objectives and scope of this study are outlined in this chapter.

Chapter 2 comprises a literature review of the findings and knowledge obtained in previous studies on the properties of concretes containing CSAC binder, with and without other binders. These findings are summarised to identify current research gaps and highlight the research significance and the objectives of this study. Due to the lack of adequate information on the strength development trends of concrete containing CSAC binder, equations are established to enable the estimation of the compressive strengths at critical ages of concretes containing various combinations of CSAC and other binders. Attempts are also made to develop predictive models to determine the shrinkage performance of concretes containing CSAC binder, as this is another important performance parameter. These attempts are made by reviewing current predictive models given in well recognised technical reports. However, although these models are widely used for concretes containing OPC (types I, II or III), as specified in ASTM C150-07 ("Standard Specification for Portland Cement") [19], their applicability to concretes containing CSAC binder, or combinations of CSAC with OPC, PFA and GGBS binders, has not previously been verified. Therefore, based on the experimental results obtained by conduction the tests to ASTM C157/C157M-08 ("Standard test method for length change of hardened hydraulic-cement mortar and concrete") [20], correction factors are derived for CSAC and other binders for use in the predictive models described in the literature. Then, the fire-resistant properties of concretes are investigated. As compared to the short-to-medium term parameters of strength and shrinkage performance, which are key for structural design, fire resistance affects the long-term durability and sustainability of concrete structures exposed to fire. Strength reduction factors, which are quotients of compressive strengths before and after exposure to different elevated temperatures, are given in design codes for structural concrete. The Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] is therefore reviewed, and the strength reduction factors it states are compared with the test results obtained in this study. This enables a comparison of the fire-resistant properties of CSAC concretes to those of OPC concretes.

Chapter 3 outlines the test regime that was used to collect the required test data or perform measurements to achieve the research objectives of this study. Concrete mixes containing CSAC binder alone and in combination with OPC, PFA and GGBS binders are designed and assigned identifying codes. The raw materials to be used in the concrete mixes are described. Reference test standards and the associated test procedures, including concrete mixing, sampling, specimen preparation, specimen curing and subsequent testing and measurement methods, are elaborated. The experimental methodologies and analytical methods used to examine the test results are described.

Chapter 4 focuses on a study of the 1-year strength development trends of concretes formed from mixes containing various binder combinations. The research significance of this study area is discussed in detail, and the test results are reported and analysed to reveal strength development trends. The contribution of each binder to strength development at different stages is also discussed. Predictive models for strength prediction at critical concrete ages are established for concretes containing various binder combinations. Conclusions are drawn on the research achievements, and the limitations to the use of the predictive models are identified. The results presented in this chapter have been published in a paper entitled '1-Year development trend of concrete compressive strength using calcium sulfoaluminate cement blended with OPC, PFA and GGBS' in *Construction and Building Materials* 198 (2019), pp. 527–536.

In Chapter 5, a study of ultimate shrinkage development in concretes containing CSAC binder blended with OPC, PFA and GGBS binders is presented. Predictive models for ultimate shrinkage given in well recognised literature are referenced, and a correction factor for OPC binder that is provided in the literature is verified by comparison with the test results. In addition, correction factors for CSAC, PFA and GGBS binders are derived for use in the predictive model and verified by comparison with shrinkage measurements obtained in this study. The established predictive models and correction factors are further validated by comparing the calculated ultimate shrinkage values of concretes with their measured shrinkage values at the same ages. Conclusions are drawn on these research achievements, and the limitations to the use of the predictive models are stated. The findings of this chapter have been published in a paper entitled ‘Model for predicting shrinkage of concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS’ in the *Journal of Building Engineering* 32 (2020), p. 101671.

In Chapter 6, the results from testing the fire-resistant properties of concretes incorporating CSAC binder, either alone or blended with OPC, PFA and GGBS binders, are described. The 28-day compressive strengths of specimens made from the concrete mixes before and after 2-h exposure to an elevated temperature of 300°C are presented and discussed. The results are used to calculate the strength reduction factors, calculated as the ratios of concrete strength after elevated temperature exposure to that before, for comparison with those given in the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14]. Variations in strength reduction factors that reflect the fire-resistant properties of concrete formed from mixes containing various binder combinations are compared with those of concretes formed from mixes containing only OPC binder. The conclusions of these explorations, and their limitations, are then elaborated. Based on the findings on the fire resistance characteristics of concretes incorporating CSAC as a binder, it is recommended that design engineers and concrete engineers adequately consider the fire safety of such concretes if they are used for structural elements in the indoor environments of buildings. A manuscript reporting the research results of this chapter is under preparation, and will be submitted to a top journal for publication.

In Chapter 7, the experimental results obtained in this study are summarised and discussed. The key findings and research achievements are outlined, and conclusions are drawn.

In Chapter 8, the applicability of the study findings to real-life construction purposes is evaluated. and the limitations to the use of concrete incorporating CSAC binder are given, based on the experimental results obtained. Without prejudice to the results obtained and the predictive models derived in this study, limitations to the scope and associated test regime of this study are also identified. In association with these limitations, the attainment of the planned research objectives is reviewed, and the remaining knowledge gap is identified. With reference to this remaining knowledge gap, recommendations for further study are given.

Chapter 2 Literature Review

2.1 Properties of concrete containing CSAC and other binders

OPC remains the main binder used in modern concrete mixes, but its incorporation with supplementary binders, such as PFA and GGBS, to enhance the mechanical properties and durability of concretes has become increasingly popular [1]. CSAC was first developed in China in the 1960s and has been further developed in the past few decades [2, 3]. The rapid strength gain and high volumetric stability properties of CSAC concrete [4] are recognised as superior to those of conventional OPC concrete, and CSAC consequently becomes a popular binder for use in concretes for applications that require these properties.

Pera et al. [3] and Glasser et al. [4] discussed the roles of the main ingredients of CSAC, namely belite (C_2S), ye'elimite ($Ca_4Al_6O_{12}(SO_4)$) and gypsum ($CaSO_4$), as these are the primary contributors in the hydration process to form ettringite crystals realizing the early strength development and volumetric stability of CSAC concretes. However, only concretes containing CSAC as a sole binder were studied, and early strength was found to be proportional to the CSAC content. In addition, the 28-day compressive strengths of these CSAC-only concretes were found to be similar to those of OPC-only concretes with the same binder content, but those studies were not extended to later ages. Likewise, concretes containing CSAC blended with other binders, such as OPC, PFA and GGBS, have seldom been examined.

Winnefeld and Lothenbach [5] experimentally examined and developed thermodynamic modelling for the hydration process of CSAC in concrete. They found that large amounts of heat were generated during hydration, immediately after the final concrete-stiffening period, and that the amount of heat was proportional to the CSAC content. This is attributable to the early formation of ettringite crystals, which are key to the rapid gain in strength of CSAC concrete at very early ages (i.e., a few hours). Similar results and conclusions were reported by Bernardo et al. [6], who instead performed a porosimetric study of a CSAC paste cured at early ages.

From these previous studies, a focus on the early strength performance of CSAC concretes can be observed. In contrast, the long-term strength development of CSAC concrete, particularly in comparison with that of OPC concrete, has commonly been ignored. One objective of this study was to fill this knowledge gap via an experimental approach to determine the strength development trends of concretes containing CSAC binder, both alone and in combination with other binders. An additional objective was to attempt to derive equations to estimate the compressive strengths of these concretes at critical ages of up to 365 days, beyond which only minor changes in strength are expected.

In a study by Yang [7], the actions of ettringite and the conditions required for its formation in concrete were identified, and the mechanism of ettringite crystallisation in the hydration process of CSAC in concretes was clearly explained. Furthermore, the advantages of the development of early strength due to ettringite crystallisation, which also results in some expansion and thus partially compensates for shrinkage in CSAC concrete, were elucidated. Nevertheless, as the stability of ettringite crystals in CSAC concrete is uncertain, any change in their morphology during exposure to unfavourable conditions (e.g., elevated temperature) may adversely affect the characteristics of the concrete, such as its built-up strength. Therefore, to further investigate the stability of ettringite crystals in CSAC concrete and their possible effects on its compressive strength, the fire resistance capability of CSAC concretes was experimentally examined as part of the work described in this thesis. The resulting strength reduction factors at a designated elevated temperature are compared with those given in current design codes for ordinary (non-CSAC) concretes.

Previous studies only examined the characteristics of early-age CSAC concrete, but have not explored its long-term performance in terms of mechanical strength and shrinkage development at ages beyond 28 days.

The mechanical activation of GGBS–OPC binder combinations and the durability of the resulting concretes was studied by Kumar et al. [8] and Osborne [9], but the effect of GGBS combined with CSAC binder was not examined. In addition to the studies of Babu et al. [10] and Oner et al. [11] on the properties of concretes containing supplementary binders (PFA and GGBS) blended with OPC binder, Xi et al. [21] investigated the influence of these supplementary binders on the properties of concretes that also contained CSAC binder. However, all of these previous studies focused only on strength properties up to 28 days. Dachtar [22] used only CSAC as a binder in investigations of structural concrete, and also focused only on early strength development and strength performance up to 28 days. Yi et al. [23] explored measures for improving the strength development of CSAC concrete at later ages, but did not explore the influence of supplementary binders. As the long-term strength characteristics of concrete are among the most important factors that affect the durability of a concrete structure, and given that the properties of concretes containing OPC binder alone or in combination with PFA and GGBS binders are well-known, a similar examination of CSAC concretes is warranted.

2.2 Strength performance of concretes related to binder combinations

Neville [24] attributed the influence of binder materials and aggregates to the shrinkage performance of concretes with the same water-to-binder ratio. The ability of aggregates to reduce shrinkage depends on their elastic properties or compressibility. Granitic aggregate, which has a high modulus of elasticity and thus low compressibility, was used in nearly the same proportions in all concrete mixes in this study. Its effect on the strength and shrinkage development of concrete is considered negligible, compared to the influence of binder combinations in the concrete mix. Neville [24] further confirmed that the properties of cement had little influence on the extent of the resulting concrete shrinkage. However, he noted that if two concretes contained different proportions of cement but the same water-to-binder ratio, the concrete with the higher proportion of cement would exhibit a greater extent of shrinkage due to the formation of a larger volume of hydrated cement paste, which is prone to shrinkage. Neville [24] also stated that the inclusion of a high percentage of either PFA or GGBS binder in a concrete mix would increase shrinkage, but did not give the threshold percentages. Nevertheless, high-volume replacement of OPC by PFA or GGBS binders is not yet popular in concrete mix designs, except in some special applications such as massive concrete dams. Most concrete mix designs in current Hong Kong projects contain commonly adopted proportions of PFA (25–35%) and GGBS (35–65%) in binder combinations.

Zhou et al. [25] investigated the compressive strength and shrinkage properties of concrete containing PFA and GGBS in addition to OPC binder systems. Their results show that concretes with PFA binder as a partial replacement for OPC binder had a significantly lower compressive strength at the age of 28 days than concretes containing only OPC binder or OPC–GGBS binder blends. In contrast, when 30% of OPC binder was replaced by GGBS binder, the resulting concrete had a higher compressive strength at 28 days than the pure OPC concrete. However, as the proportion of GGBS binder was increased from 30% to 70%, the 28-day compressive strength of the corresponding concrete decreased to less than that of pure OPC concrete. Zhou et al. [25] also showed that concretes in which OPC had been replaced by PFA or GGBS binders exhibited less shrinkage at 28 days than that of pure OPC concrete, with the effect of GGBS being the greatest. However, as only 28-day compressive strength and shrinkage results were studied, the latent effects of PFA and GGBS binder that may contribute to strength and shrinkage development in concrete remain unexplored. In this regard, such experimental studies must be extended to later ages to explore the long-term or ultimate properties of such concretes, as these are essential for concrete durability and structural design considerations.

Chen et al. [26] found that blending OPC and CSAC in mixed neat cement paste would accelerate the hydration of the binder materials. It was concluded in their study that OPC and CSAC had their own distinct characteristics and were not able to be used together under general circumstances. Nevertheless, it was also mentioned in their conclusion that the two cements could be used together in different ratios in the binder composition for achieving specific requirements with the aid of appropriate admixtures. Wang et al. [27] had similar findings that the combination of OPC and CSAC would result in shortened setting time of the combined neat cement paste. Their findings also verified that the 30:70 proportion of OPC and CSAC would give maximum strength achievement at 28 days comparing with other proportions at 28 days while the setting time of the combined neat cement paste was found to reduce by 14 minutes. In addition, Wang et al. [27] speculated the shortening of setting time of OPC in combination with CSAC was caused by the seizing of calcium sulphate in OPC by CSAC due to higher chemical activity of the latter. Martin et al. [28] shared similar findings in their study that there was no strength loss for PFA contents up to 15% in CSAC/PFA blended mixes but significant strength reduction was recorded with increasing PFA addition.

Ioannou et al. [29] found that the 28-day compressive strengths of concretes containing CSAC and PFA binder blends were inversely proportional to the percentage of CSAC that was replaced by PFA. Although the mechanism of CSAC/PFA binder matrix hydration was not discussed, there was much larger rate of decrease in the 28-day strength of concrete as the PFA content increased, compared to that of the OPC/PFA-containing concretes. This indicates that the pozzolanic properties of PFA were not activated by CSAC until the age of 28 days, akin to the effect of the hydration product of OPC ($Ca(OH)_2$) on PFA. However, Ioannou et al. [29] confined their study to concretes containing CSAC/PFA binder combinations. The effects of triple-blend binder combinations of CSAC/OPC/PFA and other binder combinations incorporating GGBS remain to be explored.

Most previous studies on the strength and shrinkage characteristics of concrete focused only on developmental trends up to the age of 28 days, as this is the age at which the indexing quality criteria of design codes for concrete are set for structural design purposes. Nevertheless, developmental trends for these two quality parameters at ages beyond this indexing age are also important for assessments of durability and other long-term performance parameters of concrete structures. In conventional concretes that contain OPC as the sole binder, strength and shrinkage parameters are expected to be close to full maturity at the age of 28 days, with only insignificant increases afterwards. However, the pozzolanic reactions in concretes in which OPC has been partially replaced by the supplementary binder materials PFA or GGBS are expected to ongoing to age far beyond 28 days, leading to continuous increases in strength until cessation of the pozzolanic reactions. In addition, the short-term and long-term effects of incorporating CSAC in binder combinations with OPC, PFA and GGBS remain to be explored.

2.3 Shrinkage performance of concretes related to binder combinations

Shrinkage is also an important parameter in structural considerations, as excessive shrinkage may lead to problems in concrete members, such as cracking or excessive deformation, or prestress loss from prestressed concrete [17]. Similarly, excessive shrinkage of a repair material (concrete or mortar) may also induce excessive shear-bond stress at the interfaces of concrete repair works, thus causing detachment of the repair material from the parent concrete. The shrinkage of concrete is therefore considered a key parameter of structural design for the determination of design loads and the provision of shrinkage-resistant reinforcement at appropriate locations [12-14]. Both the ACI 318-14 ("Building code requirements for structural concrete – Commentary on building code requirements for structural concrete") [12] and the BS EN 1992-1-1:2004 + A1:2014 ("Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings") [13] state that shrinkage, in addition to creep and temperature effects, must be considered in designs to control cracking and prevent structural failure.

Brooks [16] and Kristiawan [17] gave similar definitions for shrinkage in concrete, with both essentially stating that shrinkage is the volume reduction of concrete that occurs when it is subject to a loss of moisture, which is due to moisture migration to the environment and internal consumption during hydration processes. Brooks [18] studied the shrinkage of concrete and found that it was reduced by replacement of OPC with PFA and GGBS. However, only the 28-day shrinkage values of specimens were compared; their long-term shrinkage performance was not considered. In contrast, Kristiawan [17] found that the shrinkage in concrete at 56 days was not significantly affected by the replacement of OPC with PFA and GGBS binders if the water-to-binder ratio remained unchanged. Neville [24] reached similar findings to Kristiawan [17], determining that neither creep nor shrinkage in concrete were fundamentally affected by the use of PFA. Neville [24] further added that the overall shrinkage of concretes was unaffected by the replacement of OPC with GGBS binder, although this sometimes led to a small increase in initial shrinkage. Yang [7] reported the expansive effect of ettringite crystals formed at the initial stage of hydration in concretes that incorporated CSAC as a binder, but did not examine the combined effect of this expansion and concrete shrinkage.

The early expansion effects of ettringite crystals formed during CSAC hydration are well known, but there has been little investigation of the long-term shrinkage performance of concretes containing CSAC as a binder, or blends of various combinations of CSAC and OPC, PFA or GGBS binders.

2.4 Current predictive models and design codes and their applicability to concretes containing binders other than OPC

Building codes in the United States [12], the European Union [13] and Hong Kong [14] provide basic the performance parameters, including those related to compressive strength and shrinkage, of various grades of concretes for structural use. However, these performance parameters refer only to concretes containing OPC binder, or to combinations of OPC with PFA or GGBS binders. In ACI 209.2R-08 ("Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete") [15] published by the American Concrete Institute, several predictive models are given for estimating the shrinkage performance of concretes at various ages up to their ultimate values. Among the standard test methods mentioned in the United States' design code [12], the European Union design code [13] and the Hong Kong design code [14], the compressive strength test method stated in the Hong Kong Construction Standard 1: 2010 (CS1: 2010) [30] and the shrinkage test method given in ASTM C157/C175M-08 ("Standard test method for length change of hardened hydraulic-cement mortar and concrete") [20] were judged most appropriate for use in this study. Section 10 of the Hong Kong Construction Standard 1: 2010 [30] specifies a curing temperature of 27 ± 3°C for specimens prepared for compression testing, which is higher than that specified in the U.S. and European test standards (20 ± 2°C) and is designed to suit the different climatic environment in Hong Kong. In the method for testing the length-change of hardened concrete described in ASTM C157/C175M-08 ("Standard test method for length change of hardened hydraulic-cement mortar and concrete") [20], the test age may be prolonged beyond the nominal age of 28 days, provided that the temperature (23 ± 2°C) and relative humidity (50 ± 4%) of the curing environment are maintained.

Brooks [16] proposed methods for predicting the elasticity, shrinkage and creep of concrete based on ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. However, the predictive models provided in this ACI Guide are only applicable to cement types given in ASTM C150-07 ("Standard specification for Portland cement") [19].

Overall, most of the existing predictive models for estimating the strength and shrinkage performance of concrete are only applicable to concretes that contain conventional binders, such as OPC. Thus, given the increasing popularity of concretes that contain various combinations of CSAC, OPC, PFA and GGBS binders, there is an immediate need for predictive models that are applicable to estimating the two key quality parameters (strength and shrinkage) of these concretes, as these would enable engineers to determine the expected quality performance of these concretes in structural use.

2.5 Fire resistance of concretes given in current design codes

Fire resistance is another crucial property of concretes with regard to building safety under fire, as emphasised in design codes [13, 14]. Thus, to inform structural engineers, strength reduction factors for concretes exposed to various elevated temperatures that simulate exposure to fire are given in design codes [13, 14]. Again, however, these strength reduction factors were developed for OPC concrete, and their applicability to concretes containing multiple binders is uncertain.

Qian and Sun [31] studied the mechanical properties of high-strength concrete after exposure to fire, and concluded that there was a risk of spalling under fire conditions. This was attributed to the high density of the concrete, which would leave too little volume to relieve the vapour pressure of moisture generated by exposure to fire. The experimental findings of Tang and Lo [32] on the mechanical and fracture properties of normal-strength concretes and of high-strength concretes containing fly ash after exposure to high temperatures were similar to those of Qian and Sun [31], and also showed that normal-strength concrete has a much lower risk of spalling than high-strength concrete. These two studies focused on the risk of spalling under fire exposure, but did not examine the effect of fire on the strength reduction factors of concretes containing OPC and PFA binders.

Elsanadedy [33] developed two regression-based models for the assessment of the residual compressive strength of high-strength concretes, which were defined as concretes having a compressive strength of 6,000 psi (~41 MPa) and containing binder combinations of OPC blended with less than 15% of PFA by weight of cement. The two models are functions of the elevated temperatures alone, irrespective of the actual binder combinations, but within the limitation of PFA binder content. This was actually less than the proportion of PFA (25–35%) commonly used in concrete mix designs for concrete structures that benefit from the advantageous properties of PFA. Therefore, there is a need for an appropriate model to enable assessment of the residual compressive strength of concretes containing more commonly used combinations and proportions of various binders.

Notably, there has been less research on the fire-resistant properties of concretes containing combinations of CSAC and other binders than on their general strength and shrinkage properties. This is a concern, as it is crucial that the fire-resistant properties of concretes containing CSAC as the sole binder, or as one of several binders, are known. Specifically, the strength reduction factors of such concretes at certain elevated temperature levels must be known to maintain the structural integrity of, for example, an entire cast structural element or to repair a large-scale structural element. The strength reduction factors given in current design codes for CSAC concrete must therefore be verified.

Chapter 3 Methods and Materials

3.1 Development of concrete mixes for study

3.1.1 Raw materials

CSAC containing 80% CSAC clinker and 20% anhydrous $CaSO_4$, which belongs to the belitic type with high early strength and expansive characteristics, was supplied by CTS Cement Corporation (CA, USA). OPC conforming to Class 52.5N Type 1 as specified in ASTM C150-07 ('Standard Specification for Portland Cement') [19] was supplied by Yue Xiu Cement Co., Ltd (Hong Kong). PFA conforming to BS EN 450-1: 2012 (Fly ash for concrete. Definition, specifications and conformity criteria") [34] and GGBS conforming to BS EN 15167-1: 2006 (Ground granulated blast furnace slag for use in concrete") [35] were supplied by Hong Kong China Light and Power Co., Ltd. and K-Wah Building Materials Co., Ltd. (Hong Kong), respectively. Key chemical compositions of the 20 concrete mixes containing various combinations of CSAC, OPC, PFA and GGBS binders are shown in Table 3.1. Coarse and fine granitic aggregates conforming to BS EN 12620: 2013 (Aggregates for concrete") [36] were both obtained from Sun Ling Quarry, Jiangmen, China. To achieve the required workability and adequate workable time for casting (which is determined to be 45 min for on-site operations), the water-reducing agent SP8S and the hydration stabiliser Delvocrete (both supplied by BASF Hong Kong), which both conformed to BS EN 934-1: 2008 (Admixtures for concrete, mortar and grout. Common requirements – Part 1: Common requirements) [37], were used. Dosages of these two admixtures for concrete mixes with various binder combinations were adjusted to achieve the target workability of a 150 ± 25 mm slump and an initial stiffening time of 60 ± 10 min. All batches were mixed in laboratory conditions at 25 ± 3°C and a relative humidity of not less than 50%, in accordance with Section 11 ("Mixing and sampling fresh concrete in the laboratory") in the Hong Kong Construction Standard 1: 2010 [30].

3.1.2 Concrete mix design and mix identification

Twenty concrete mixes were designed (Table 3.2) to provide a range of concretes containing various combinations and proportions of CSAC, OPC, PFA and GGBS binders that are used in practical applications. Mix identifications (mix IDs) were assigned to each concrete mix according to the proportions of each binder they contained, using the format (% of CSAC)/(% of OPC)/(% of PFA)/(% of GGBS). For instance, the mix ID of 37.5/37.5/25/0 represents a concrete mix containing a binder comprising 37.5% CSAC, 37.5% OPC, 25% PFA and 0% GGBS. All of the concrete mixes were designed to exhibit a characteristic strength of 45 MPa, a target workability of a 150 ± 25 mm slump, a water-to-binder ratio of 0.42 and a binder content of 420 kg/m^3 of concrete. To enable adequate time for placement operations in real-life applications, the target initial-stiffening time was 60 ± 10 min. As the initial stiffening time is primarily affected by the proportion of CSAC in a binder, this time was adjusted by regulating the dosage of Delvocrete according to the CSAC content in each concrete mix. Concrete mixes containing 100% CSAC binder and 100% OPC binder were used to generate reference results for comparison with those obtained from testing concrete mixes containing various combinations of the four binders (CSAC, OPC, PFA and GGBS). Other concrete mixes were designed to contain various combinations of the four binders with consideration of practical use of the concrete mixes and the purpose for studying the effect of each binder material on performance of compressive strength, shrinkage and fire resistance. Among the mix designs, the most commonly used proportions within the % range stipulated in local concrete specifications of the two supplementary binders, PFA (25%, 35% and 45%) and GGBS (35% and 65%), were used for blending with CSAC and OPC. The OPC/PFA blended concretes mostly used in local construction projects (Mixes 0/75/25/0 & 0/65/35/0) are also included in the study for comparisons with other concretes incorporating CSAC and other binder materials.

The use of PFA–GGBS blends in concrete mixes remains prohibited in Hong Kong, although it has become common practice in Europe and China. Thus, only one of these two supplementary binders was included as a partial substitute for a key binder (either OPC or GGBS) in concrete mix designs in this study. This ensures that the models obtained for the prediction of compressive strengths and ultimate shrinkage are suitable for the analysis of the properties of the most commonly used concrete mixes in Hong Kong.

3.1.3 Test plan, test procedures and test standards

Standard 100-mm^3 cubic specimens of each concrete mix were cast and tested in accordance with Section 7 of the Hong Kong Construction Standard 1: 2010 [30] at the ages of 2, 4 and 6 h and 1, 7, 14, 28, 90, 180 and 365 days, with two cubes of each concrete tested for each age. The compressive strength results of concretes containing similar combinations of binder materials are compared to investigate the strength development trends of each combination.

Three 75-mm × 75-mm × 285-mm prisms of each concrete mix were also cast, and their changes in length with respect to their initial lengths measured at 24 ± 1 h were measured at the ages of 7, 14, 28, 90, 180 and 365 days, in accordance with ASTM C157/C157M-08 ("Standard test method for length change of hardened hydraulic-cement mortar and concrete") [20]. The resulting shrinkage data for the specimens are plotted against the age of measurement to reveal the shrinkage development trends of the concretes. These trends are analysed to determine the effects of various binder combinations and each binder. The shrinkage data at 365 days are used to predict the ultimate shrinkage values of each concrete, based on the equation given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. Correction factors (K factors) are then devised for each binder for inputting into the GL2000 model given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], and verified by comparison with the predicted ultimate shrinkage values of the concretes containing these binders. These verified K factors for the four binders are suitable for estimating the ultimate shrinkage values of concrete mixes containing various binder combinations according to the proportions of each binder in the total binder content.

Two additional 100-mm^3 cubes of each concrete mix were cast for compressive strength tests after a standard curing period of 28 days in accordance with Section 10 of the Hong Kong Construction Standard 1: 2010 [30] followed by a 2-h exposure to an elevated temperature of 300°C in the furnace at the Concrete Laboratory of the Hong Kong Polytechnic University, during which time the temperature was increased from room temperature to 300°C at a rate of approximately 20°C per minute. The differences between the 28-day compressive strengths of concrete specimens that were and were not exposed to 300°C are regarded as representing the reduction in strength of the specimens after fire exposure. The quotient of the compressive strength results of each specimen before and after exposure to 300°C at 28 days is calculated, and is regarded as the strength reduction factor of each concrete mix at this temperature. The strength reduction factors of all twenty concrete mixes are calculated and compared with those given in the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] to evaluate the fire resistance capability of concretes containing various combinations of binders with respect to that of ordinary concrete containing OPC as the key binder.

(a) Mixing procedure and equipment

The ingredients of each concrete mix were batched in accordance with the mix proportions listed in Table 3.2 and the laboratory mixing method specified in Section 11 of the Hong Kong Construction Standard 1: 2010 [30]. The binders and admixtures were stored in airtight sealed bags and bottles, respectively, to maintain them in stable environmental conditions prior to conducting the mixing operations. The aggregates were stored in bulk for air drying at laboratory temperature conditions (25 ± 5°C), as recommended in the Hong Kong Construction Standard 1: 2010 [30]. To control the quantity of mixing water in the designed mixes, the moisture contents of the aggregates were tested in accordance with the method stated in Section 11 of the Hong Kong Construction Standard: 2010 [30]. The volume of inherited moisture in the aggregates was compensated for by reducing the mixing water by the same volume, such that the total volume of mixing water in the designed mix proportion, in which the aggregates were assumed to be in a saturated surface dry condition, was maintained. A pan mixer with a capacity of 0.05 m^3 was used for mixing concretes, and the volume of each batch was 0.03 m^3, which was 60% of the mixer capacity. This was done to prevent overloading or underloading of the mixer, which might have affected the mixing efficiency. All of the ingredients for each mixture were weighed with electronic scales, loaded into the pan mixer and mixed for approximately 3 minutes, which ensured thorough mixing. All of the specimens were prepared and tested in accordance with the test regime given in Table 3.3. All mixing, sampling and specimen preparation procedures were conducted under laboratory conditions at an ambient temperature of 25 ± 5°C and relative humidity of not less than 50%, as required by Section 11 of the Hong Kong Construction Standard 1: 2010 [30].

(b) Casting and curing of 100-mm^3 cubes for compressive strength tests

All of the 100-mm^3 test cubes were made in accordance with Section 7 of the Hong Kong Construction Standard 1: 2010 [30]. The concrete materials were added to 100-mm^3 steel moulds in two layers of similar thickness. Each layer was compacted by sitting moulds on a vibrating table that was vibrated at a minimum frequency of 40 Hz (2,400 cycles per minute) for approximately 15 s, with the mould firmly held against the table to achieve full compaction of the concrete. Excess concrete (above the upper edge of the mould) was removed, and the surface was carefully levelled with a steel trowel. The cast cubes were demoulded on the following day and cured at the laboratory of Yue Xiu Concrete Co., Ltd. at 27 ± 3°C in a water curing tank equipped with a circulation pump to ensure good water circulation. Two 100-mm^3 test cubes of each concrete were tested at each designated age in accordance with Section 12 of the Hong Kong Construction Standard 1: 2010 [30], using the calibrated compressive-strength testing machine in the same laboratory. The average of the compressive strengths of the two 100-mm^3 test cubes of each concrete at each age is taken as the compressive strength for a concrete mix at that age.

(c) Casting and curing of concrete prisms for measurement of shrinkage in terms of length change

Three concrete specimens with a 75-mm square cross section and 285-mm length were prepared from each concrete mix in accordance with ASTM

C157/C157M-08 ("Standard test method for length change of hardened hydraulic cement mortar and concrete") [20]. The batched ingredients were mixed in accordance with the procedures described in Section 3.1.3 (a) above, and each concrete was cast in 75-mm × 75-mm × 285-mm steel moulds in two approximately equal layers. Each layer of the mixture was compacted by sitting the moulds on a vibrating table, as described in Section 3.1.3 (b). Excess material was removed with a straightedge. Immediately after the completion of specimen preparation, the mounting device for the mould was loosened and the gauge studs were held in position at each end of the mould to prevent any restraint of the gauge studs before demoulding. The initial lengths of the concrete prisms were measured at 24 ± 1 h after demoulding, and the specimens were then cured in a chamber at 23 ± 2°C and a relative humidity of 50 ± 4%, as specified in ASTM C157/C175M-08 ("Standard test method for length change of hardened hydraulic cement mortar and concrete") [20]. Afterwards, the lengths of the concrete prisms were measured at the designated ages listed in Table 3.3, and changes in the lengths of the specimens with respect to their initial lengths were regarded as expansion (positive) or shrinkage (negative).

3.2 Analytical methods

Based on the experimental results, predictive models are established for estimating the compressive strengths of the test specimens at designated ages and the ultimate shrinkage values for concrete mixes containing various binder combinations. The results are summarised in tables for easy reference. Developmental trends in the compressive strength and shrinkage values are revealed by plotting these data against the corresponding test ages for concretes containing various binder combinations. The effects of different binders on the hydration processes and the developmental trends in the compressive strengths and shrinkage of concretes are analysed. Correlation curves are plotted to derive the correction factors for individual binders. An initial value is assumed for use in the established predictive models. After an iterative trial-and-error process, correction factors that best fit the predictive models containing the test results are obtained. These results are plotted in correlation curves, and the coefficients of determination of the lines of best fit are calculated. The reliabilities of the derived correction factors are validated by comparison with the coefficients of determination of the correlation curves, with a line of best fit above 0.8 serving as the validation criterion. The equations given in the technical report of ACI 209-2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15] for predicting shrinkage at different concrete ages are also used for validation. These equations are used to predict shrinkage at different concrete ages using the predictive models developed above, and the results are compared with the measured shrinkage results.

To examine the fire resistance abilities of concretes containing CSAC in combination with various other binders, 100-mm^3 test cubes were made and examined in compressive strength tests at an age of 28 days, with or without prior 2-h exposure to a temperature of 300°C, as described previously. The 28-day compressive strengths of concretes after exposure to this elevated temperature are divided by the 28-day compressive strengths of concretes not exposed to this elevated temperature to obtain the strength reduction factors of each concrete, which are compared with those given for ordinary OPC concrete in Table 3.5 of the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14]. The comparison results indicate the fire-resistant properties of concretes that incorporate CSAC as a binder. This is important for determining the possible strength reductions in such concretes at elevated temperatures due to the deterioration or decomposition of ettringite crystals, which may lead to fire safety problems. These aspects must be considered when concretes containing CSAC binder are to be used in the indoor environment of a building.

Table 3.1 Key compositions of binders used

Binder	Main Compositions					
CSAC	Clinker: 82%			Addition: 18%		
	Ye'elimite	Belite	Others	Anhydrous $CaSO_4$		
	58%	12%	12%	18%		
Other binders	Main Compositions					
	CaO	Al_2O_3	MgO	Fe_2O_3	SiO_2	Others
OPC	65	6	2	4	20	4
PFA	2	30	2	8	48	10
GGBS	40	12	8	0.5	35	5

Note: $CaSO_4$ (Calcium Sulphate); CaO (Calcium Oxide); Al_2O_3 (Aluminium Oxide); Fe_2O_3 (Ferric Oxide); SiO_2 (Silicon dioxide)

Table 3.2 Binder combinations and admixtures used in concrete mix design

Mix	Binders (in kg/cum of concrete)				Admixture (in l/cum of concrete)	
	CSAC	OPC	PFA	GGBS	SP8S	Delvocrete
100/0/0/0	420	0	0	0	5.88	2.0
75/25/0/0	315	105	0	0	5.88	1.8
50/50/0/0	210	210	0	0	5.88	1.7
25/75/0/0	105	315	0	0	5.88	2.0
75/0/25/0	315	0	105	0	5.88	1.8
65/0/35/0	273	0	147	0	5.88	1.7
55/0/45/0	231	0	189	0	5.88	1.6
0/100/0/0	0	420	0	0	5.88	0.0
37.5/37.5/25/0	158	157	105	0	5.88	1.8
32.5/32.5/35/0	137	136	147	0	5.88	1.7
27.5/27.5/45/0	116	115	189	0	5.88	1.6
0/75/25/0	0	315	105	0	5.88	0.0
0/65/35/0	0	273	147	0	5.88	0.0
5/95/0/0	21	399	0	0	5.88	0.0
70/5/25/0	294	21	105	0	5.88	1.8
65/10/25/0	273	42	105	0	5.88	1.7
65/0/0/35	273	0	0	147	5.88	1.7
35/0/0/65	147	0	0	273	5.88	1.4
32.5/32.5/0/35	136	137	0	147	5.88	1.7
17.5/17.5/0/65	74	73	0	273	5.88	1.6

Note to Table 3.2:

(a) *SP8S was used to attain a concrete workability within the acceptable range for the required slump of 175 mm.*

(b) *Delvocrete stabiliser was used to regulate the workable times of concrete mixes that contained CSAC to at least 1 h, to allow for placement.*

Table 3.3 Specimens made for testing

Mix	Total no. of 100-mm^3 cubes made for compressive testing (two cubes each tested at 2, 4 and 6 h and 1, 7, 14, 28, 56, 90, 180 and 365 days)	Total no. of 100-mm^3 cubes made for compressive testing at 28 days and after 2-h exposure to 300°C	Total no. of 75-mm × 75-mm × 285-mm prisms made for shrinkage testing at 2, 7, 14, 28, 56, 90, 180 and 365 days
100/0/0/0	22	2	3
75/25/0/0	22	2	3
50/50/0/0	22	2	3
25/75/0/0	22	2	3
75/0/25/0	22	2	3
65/0/35/0	22	2	3
55/0/45/0	22	2	3
0/100/0/0	22	2	3
37.5/37.5/25/0	22	2	3
32.5/32.5/35/0	22	2	3
27.5/27.5/45/0	22	2	3
0/75/25/0	22	2	3
0/65/35/0	22	2	3
5/95/0/0	22	2	3
70/5/25/0	22	2	3
65/10/25/0	22	2	3
65/0/0/35	22	2	3
35/0/0/65	22	2	3
32.5/32.5/0/35	22	2	3
17.5/17.5/0/65	22	2	3

Chapter 4 One-year Developmental Trends in Compressive Strength of Concretes Containing Combinations of CSAC, OPC, PFA and GGBS Binders

4.1 Introduction

Concrete that contains CSAC binder exhibits outstanding volume stability and rapid early-stage strength development [2–4], and is therefore often used when substantial strength is required within a few hours [22]. However, the use of only CSAC binder may not be necessary in cases where a relatively low early-strength concrete is required (e.g., for the attainment of several MPa of strength within a few hours). Hence, binder combinations containing OPC, PFA or GGBS are often considered instead of a pure CSAC binder, which enables cost savings. In addition, PFA and GGBS are commonly used due to their lower carbon footprint, lower heat of hydration and ability for further strength increases at a later stage, as a result of hydraulic properties derived from a secondary hydration reaction with OPC [1, 8 ,9]. However, as the CSAC hydration process and the resulting hydration product are different from those of OPC [21], the effect of the hydraulic properties of PFA and GGBS in blends with CSAC are not fully understood.

Although numerous studies have examined the trends in strength development of concretes containing OPC binder blended with PFA or GGBS binders and other benefits of the inclusion of these latter binders, little research has been conducted on the long-term (up to 1-year) developmental trends in the compressive strength of concretes containing blends of CSAC and other binders [38, 39]. Dhir et al. [37] and Maring et al. [41] found that the addition (not replacement) of 5–15% by mass of PFA binder to a CSAC concrete mix led to an increase in 28-day compressive strength of up to 3 - 6 MPa in the resulting concrete, while the addition of greater amounts of PFA reduced the compressive strength. Due to the lack of reliable references on the strength development trends of concretes containing pure CSAC or CSAC blended with other binders, numerous trials are often required to identify binder combinations that will ensure concretes with a good early strength performance and 28-day and long-term strengths. The early strength performance of a concrete formed from a given mix may be rapidly determined by laboratory testing at the planning stage, but a much longer time is required to verify the 28-day strength and long-term strength, which are more important properties in terms of structural safety.

The test results obtained in this study are used to establish empirical equations for predicting the strength characteristics of concrete mixes containing various binder combinations at early (2–6 h) and later ages (28 and 365 days). The 365-day strength is taken to be the long-term strength performance parameter in this study since the compressive strength development trends of all the concrete mixes show that the development rates at this age become rather slow and little % gain is expected afterward. Thus, cost estimations and carbon footprint calculations for concrete mix designs are largely handled at the planning stage. Predictive models and the long-term strength development performance of a concrete may be used to determine the probable early- and later-age strength of a concrete, thereby preventing the misuse of CSAC in combination with other binder(s) and enabling related concerns to be addressed.

An objective of this study was to investigate the strength development trends at different ages of concretes containing various binder combinations of OPC, PFA and GGBS with CSAC, namely at (1) early ages (2–6 h), (2) 28 days and (3) 365 days. These trends were to be used to derive empirical equations for the prediction of early and later strengths of concretes containing various binder combinations incorporating CSAC, for use by engineers at the design and planning stages of projects.

4.2 Research significance

The designing of concrete mixes to form concretes with a desired compressive strength performance is often a trial-and-error exercise based on previous results. Past strength performance records of concretes can be used to estimate the potential strengths at critical age(s) of concretes formed from designed ordinary concrete mixes containing commonly used binder compositions. In some cases, trials may be performed to validate the estimated strength performance at 28 days of a concrete that is intended for large-scale use, as this performance is regarded as the characteristic strength for structural design purposes. This process is time consuming, particularly when repeated trials are required. Moreover, past strength performance records are usually unavailable for concretes formed from designed mixes containing CSAC and other binder(s), which means that comprehensive trials must often be performed to confirm that these mixes can be used to form concretes with the desired properties. In such scenarios, reliable predictions of the compressive strength (the key performance parameter) of concretes formed from the planned mix design enhance the confidence of design engineers.

In this study, the contributions of CSAC, OPC, PFA and GGBS binders to the hydration process and the interactions of these binders were determined, and their corresponding strength factors are derived. These strength factors, together with the developed strength prediction equations, will enable structural engineers and concrete engineers to make reasonable estimations of the strength performance of a concrete formed from a designed concrete mix that contains the most common combinations of CSAC, OPC, PFA and GGBS binders. This will minimise the need for time-consuming mix trials before application. The strength factors of different combinations of binders can be validated by comparison with the strength results at early ages and at 28 days, prior to direct adoption or adoption after slight adjustment of these mixes. Test cubes of concretes can also be cast for the determination of strength factors at later ages, such as 56, 90, 180 or up to 365 days, to enable continual monitoring of the applicability of the developed strength factors to new combinations of binders. In most applications of concrete, however, confirmation of the 28-day compressive strength is deemed adequate.

4.3 Methodology

As discussed in Chapter 3, twenty concrete mixes containing various binder combinations (as listed in Table 3.2) were tested. All twenty concrete mixes had the same design parameters: a binder content of 420 kg/m^3 of concrete, a water-to-binder ratio of 0.42, a maximum aggregate size of 20 mm, a designed slump of 150 mm and a minimum workable time of 45 min. Concretes with the designed slump of 150 mm have been proved in practical applications to have adequate workability for most applications. Given that the workable time of concretes that contain CSAC in a binder blend is inversely related to the proportion of CSAC in the blend, and that a pure CSAC concrete has a verified workable time of only approximately 15 min [5], a retarding agent was used to extend the workable times of concretes containing various binder combinations to a minimum of 45 min. This allowed time for casting after mixing is the normally required duration required on-site for concretes with substantial early-strength performance.

With reference to the test regime given in Table 3.3, twenty-two 100-mm^3 cubic specimens (two for each age) of each concrete mix were cast. These were subject to compressive strength testing at the ages of 2, 4 and 6 h and 1, 7, 14, 28, 56, 90, 180 and 365 days, in accordance with Section 12 of the Hong Kong Construction Standard 1: 2010 (“Determination of compressive strength of concrete cubes”) [30]. An average of the early strength of each concrete at 2, 4 and 6 h was regarded as the early strength performance. SEM photographs are taken for the crushed specimens at the age of 1 day to examine the morphology of concretes with different binder combinations. An early-strength prediction equation is established for estimating the early strength performance of concretes containing various proportions of CSAC binder. This equation can be used to predict the early strength performance of a concrete incorporating a blend of CSAC, OPC, PFA and GGBS binders by comparison to the known early-strength performance of a pure CSAC concrete. Similarly, equations for the prediction of the 28-day and 365-day compressive strength performance of concretes containing blends of CSAC, OPC, PFA and GGBS binders are also established.

4.4 Test results and discussions

The compressive strength test results at the ages of 2–6 h to 365 days of all concretes in this study are summarised in Table 4.1, revealing the different strength development trends of concretes formed from mixes containing various binder combinations. To facilitate analysis, the results are grouped in the binder combinations of CSAC/OPC, CSAC/OPC/PFA and CSAC/OPC/GGBS to show the different performances of various binder combinations and the contributions of each binder in each combination to strength development. The results at different ages for each group of binder combinations are plotted in Figures 4.1 to 4.3. The compressive strength development trends from early ages (2–6 h) up to 365 days of concretes containing different binder combinations (CSAC/OPC, CSAC/OPC/PFA and CSAC/OPC/GGBS) are analysed separately, due to the different hydration-process performances of these binder combinations.

The early strengths (at ages from 2–6 h to 1 day) of concretes formed from mixes containing CSAC/OPC binder blends (mixes 100/0/0/0, 75/25/0/0, 50/50/0/0 and 25/75/0/0) increased with increasing CSAC content. The strength performance of concretes containing lower proportions of CSAC but higher proportions of OPC slowly increased to a similar level as those of concretes having much higher levels of early strength. This demonstrates that concretes containing OPC and CSAC binders achieved similar long-term strengths, but at rates that varied with the relative proportions of these binders. Based on the test results, the coexistence of CSAC and OPC binders in a concrete mix did not substantially affect the hydraulic properties of each other. This agrees in principle with the findings of Chen et al. [26] and Wang et al. [27], who studied the interaction between CSAC and OPC through approaches of cement hydration degree and microstructure of hydration product respectively.

The early strength performance of concretes formed from mixes containing CSAC/OPC/PFA binder blends was found to be proportional to the relative amount of CSAC in the binder. However, the early (2–6-h) and ultimate (365-day) strength performances of concretes formed from mixes containing only CSAC/PFA binder blends (mixes 75/0/25/0, 65/0/35/0 and 55/0/45/0) decreased with decreasing CSAC content, despite the simultaneous increase in PFA content. This indicates that PFA in combination with CSAC does not give positive effect on concrete strength. This is in agreement with the findings of Maring et al. [41]. Many other studies have also proven that PFA requires $Ca(OH)_2$, which is not generated by CSAC hydration [41-44], to activate its pozzolanic reactivity leading to strength gain. Consequently, when OPC was included in the binder blend (mixes 37.5/37.5/35/0, 32.5/32.5/35/0 27.5/27.5/45/0, 70/5/25/0 and 65/10/25/0), the 28-day strengths of the resulting concretes were significantly greater than those formed from mixes containing only CSAC/PFA binder blends, and the strength increases were directly proportional to the relative amount of OPC in the binder blend. In these regards, the two binder materials of CSAC and PFA are deemed not compatible with each other when OPC is not present.

SEM photographs exhibited in Figure 4.5 to Figure 4.24 show the quantity of ettringite crystals generated in the hydration process of CSAC. It is obvious that the quantity of ettringite crystals generated is proportional to the quantity of CSAC in the binder content. It is clearly shown in the SEM photograph in Figure 4.5 for the pure CSAC concrete that the concrete matrix is only formed by ettringite crystals. For other concrete mixes with CSAC partially replaced by OPC, the concrete matrixes become a combination of ettringite crystals and calcium silicate hydrates (C-S-H), which is the hydration product of OPC, while the quantities of these two kinds of crystals are proportional to the percentages of CSAC and OPC in the binder combinations. When viewing together with the early strength development as discussed above, it proves that formation of ettringite crystals is the main source of the early strength acquired.

All of the concretes formed from the concrete mixes containing CSAC/OPC/PFA binder blends had similar strength levels after 90 days, and up to 365 days, to those of concretes formed from mixes containing only CSAC (100/0/0/0) or only OPC (0/100/0/0), and these strength levels depended on the proportion of OPC in the binder. As evidenced by the 365-day strength of the concrete formed from the mix containing only 5% OPC in its binder (mix 70/5/25/0) (64.4 MPa) compared with that formed from the mix containing 100% OPC binder (0/100/0/0) (67.1 MPa), only a small proportion of OPC binder is required to realise the hydraulic reaction-based strength gains of PFA binder. However, longer times were required to achieve strength gains in the presence of smaller proportions of OPC binder. The strength-gain process was also much slower in these cases, although the additional effects of PFA in the hydrated mix, such as nucleation effects and amorphous alumina reactions, may have assisted this process [1]. Further studies of the effect of the hydraulic reaction of PFA binder in the presence of a small quantity of OPC binder on long-term strength development in concretes would be an interesting topic for exploration by other researchers. Finally, the strength development trends of concretes made from the mixes

37.5/37.5/35/0, 32.5/32.5/35/0, 27.5/27.5/45/0, 65/10/25/0 and 70/5/25/0 further verify that the higher the OPC content in the binder of a concrete containing CSAC/OPC/PFA binder blends, the more rapidly its strength performance will match that of concretes formed from mixes containing binders comprising only OPC (0/100/0/0) or CSAC (100/0/0/0).

The early strength performance of concretes formed from mixes containing CSAC/OPC/GGBS binder blends was proportional to the relative amount of CSAC in each blend, similar to that of concretes formed from mixes containing CSAC/OPC/PFA binder blends. A comparison of the concretes formed from mixes containing the same proportions of two binders, namely CSAC/PFA and CSAC/GGBS (mixes 65/0/35/0 and 65/0/0/35), showed that concrete formed from the latter had a greater strength performance from 7 days up to 365 days. This finding demonstrates the stronger hydraulic ability of GGBS binder [8, 9] compared to that of PFA in the absence of OPC, which led to greater strength gains. Consequently, concretes formed from the two mixes containing only CSAC/GGBS binder blends (65/0/35/0 and 65/0/0/35) attained the same long-term strength level at 365 days as that of concretes formed from the two mixes containing CSAC/OPC/GGBS binder blends (32.5/32.5/0/35 and 17.5/17.5/0/65). However, the rates of strength gain in concretes formed from the former blend were slower than those formed from the latter, as the hydration processes of the latter are accelerated by the hydration product ($Ca(OH)_2$)) of OPC [8, 9]. Notably, the early strength performance (at 2–6-h) of the concrete formed from a mix containing a CSAC/GGBS binder blend (65/0/0/35) was retarded, compared with that of a concrete formed from a mix containing a CSAC/PFA binder blend (65/0/35/0) with the same CSAC content. It is recommended that future studies should confirm this phenomenon and explore its causative factors.

4.5 Establishment of a predictive model for the compressive strength of concretes containing combinations of CSAC, OPC, PFA and GGBS binders

4.5.1 Establishment of a predictive model for early-age compressive strength

Early strength results for concretes formed from mixes containing CSAC binder are shown in Table 4.2. All exhibited decreasing early-strength performance as the proportion of CSAC in the binder decreased. The hydration of OPC, which results in strength development, only occurs subsequent to its final stiffening, which normally occurs several hours after the addition of water. Moreover, most of the strength contributed by PFA and GGBS binders results from their activation by the hydration product of OPC [8, 38]. In this regard, OPC, PFA and GGBS binders are not considered to contribute to early strength development (i.e., that which develops within a few hours of being cast) in concrete.

The early strength performance of concretes containing CSAC binder depends on the composition of the CSAC clinker and the added proportion of $CaSO_4$ [2]. However, concrete mixes containing less than 25% CSAC in their binder contents do not show a measurable early strength performance [5]. Based on this and the early-strength test results obtained in this study, a mix must contain a certain proportion of CSAC binder to be able to generate a concrete that exhibits early strength within a few hours of being cast. To investigate the pattern of early strength development in concretes incorporating CSAC binder amount of 25% or more, the early strength results at 2, 4 and 6 h of concretes formed from certain mixes (Table 4.2) are analysed. The average early strengths of concretes containing CSAC binder are presented as percentages (Y) of the average early strength of the concrete formed from the mix containing 100% CSAC binder, and these Y values are plotted against their respective percentages of CSAC (X), as shown in Figure 4.4. A linear relationship is obtained, and the following correlation equation is derived from the graph, which has a coefficient of determination of 0.9707:

$Y = 1.1703X - 0.2385$, which simplifies to

$$Y = 1.17X - 0.24 \qquad \text{(Eq. 4.1)}$$

The following equation is then derived to predict the early strength performance of a concrete formed from a mix containing at least 25% CSAC in its binder:

$$S_{CSACe} = S_{CSACe\text{-}100}\,(1.17P_{CSAC} - 0.24) \qquad \text{(Eq. 4.2)}$$

where $S_{CSACe\text{-}100}$ is the early strength at 2–6-h of a concrete containing 100% CSAC binder, P_{CSAC} is the percentage of CSAC in the binder of the new concrete mix and S_{CSACe} is the early strength of a concrete formed from the new concrete mix at the same age as the concrete formed from the mix containing 100% CSAC binder.

4.5.2 Establishment of a predictive model for compressive strength at 28 days

The 28-day and ultimate compressive strengths (represented by the 365-day result in this study) are the most important mechanical properties of concrete used for structural design, and the 28-day compressive strength is normally set as the primary compliance criterion for concrete quality. The following notation is used in equations to predict the 28-day and ultimate compressive strength performance of concretes containing CSAC blended with other binders.

$S_{CSAC/OPC/X\text{-}AGE}$	the compressive strength of a CSAC/OPC/X binder blend, where X is either PFA or GGBS, OPC may or may not be present and 'AGE' may be 28 or 365 days
$S_{OPC\text{-}AGE}$	the compressive strength of a concrete containing only OPC binder at the same 'AGE' as above
$SF_{X\text{-}AGE}$	the strength factor of binder X, which is the strength contribution of X at 'AGE' to a concrete with respect to the strength of a pure OPC concrete, which is taken as 1.00
P_X	the percentage of binder X in the total binder content in a concrete mix

The results show that concretes containing CSAC blended with other binders had different compressive strengths at 28 days to those that did not contain CSAC in their binders. Compared with early strength development, the strength performance at 28 days of concretes formed from mixes containing only OPC binder is a more commonly known measure and is therefore used as the reference for predicting the 28-day strength of concretes containing other binder combinations. The nominal 28-day strength factor ($SF_{X\text{-}28}$) of each binder X is defined as the ratio of its contribution to 28-day strength to that of the same percentage content of OPC, the nominal 28-day strength factor of which (SF_{OPC-28}) is taken as 1.00.

Equations are then derived from the test results of concretes formed from mixes containing each group of binder combinations, by considering the contribution of each binder to concrete strength and the strength factor of each binder at a given age with respect to that of OPC at the same age. Concretes containing PFA or GGBS binder are dealt with separately.

The strength development at 28 days for concretes formed from mixes containing binder combinations of CSAC/OPC/PFA and CSAC/OPC/GGBS is derived using the following equation:

$$S_{CSAC/OPC/PFA-28} = (S_{OPC-28})[(SF_{CSAC-28})(P_{CSAC}) + (SF_{OPC-28})(P_{OPC}) + (SF_{PFA/GGBS-28})(P_{PFA/GGBS})] \quad \text{(Eq. 4.3)}$$

This reveals the strength factors of each binder at 28 days with respect to the strength contribution of OPC in each binder combination. The strength factors are then used to predict the strengths at specified ages of concretes formed from a mix containing various mixtures of binders.

The 28-day strength results (55.8, 56.5, 57.2 and 58.4 MPa) of the concretes formed from a mix containing only CSAC binder (100/0/0/0) and from mixes containing CSA/OPC binder blends (75/25/0/0, 50/50/0/0 and 25/75/0/0), respectively, are used in Eq. 4.3, as appropriate, to calculate strength factors for comparison with those derived from the analysis of the concrete formed from the mix containing only OPC (0/100/0/0). The average 28-day strength factor of CSAC binder ($SF_{CSAC-28}$) is calculated to be 0.95, which is used as the nominal strength factor of CSAC.

The 28-day strength results (Table 4.2) reveal that the performance of concretes formed from mixes containing PFA binder differed according to the presence or absence of OPC binder. In the OPC hydration process, $Ca(OH)_2$ is generated, which increases the alkalinity of the pore water in the concrete matrix and activates the pozzolanic reaction of PFA [1, 42]. Thus, as the hydration process of CSAC does not produce $Ca(OH)_2$ [2, 3], the pozzolanic reactivity of PFA in concretes formed from mixes containing CSAC/PFA binder blends cannot be activated. In addition, the presence of PFA led to a reduction in the 28-day strength of concretes formed from mixes containing CSAC/PFA binder blends (75/0/25/0, 65/0/35/0, 55/0/45/0). Their 28-day strength results also decreased as the CSAC binder content decreased, which was offset by a proportional increase in the PFA content. The $SF_{CSAC-28}$ value of 0.95 is used to evaluate the 28-day strength results of the concretes formed from these three mixes containing CSAC/PFA binder blends (75/0/25/0, 65/0/35/0, 55/0/45/0) by Eq. 4.3, which reveals that the strength factors of PFA (SF_{PFA-28}) 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-28}) for PFA binder in the absence of OPC binder.

In concretes formed from mixes containing CSAC/OPC/PFA binder blends, $Ca(OH)_2$ generated in the hydration process of OPC activates the pozzolanic reaction of PFA [42], resulting in increased 28-day strength. However, the 28-day strengths of concretes formed from the 70/5/25/0 and 65/10/25/0 mixes were lower than those of concretes formed from other mixes comprising the same binder combination (CSAC/OPC/PFA). This is attributed to too-low concentrations of $Ca(OH)_2$ in the binder matrixes of mixes containing 70/5/25/0 and 65/10/25/0 as a result of too little OPC being present, which thereby slowed the rate of the secondary hydration of PFA. Thus, the data of concretes formed from mixes containing low percentages of OPC binder are not used in the calculation of the strength factor of PFA in the presence of OPC. The slow rate of secondary hydration of PFA due to the low concentration of $Ca(OH)_2$ continued up to the ultimate stage (365 days), as discussed later.

The 28-day strength results for concretes formed from mixes comprising CSAC/OPC/PFA and OPC/PFA binder blends of 37.5/37.5/25/0, 32.5/32.5/35/0 and 27.5/27.5/45/0 are used in Eq. 4.3, along with $SF_{CSAC-28}$ and SF_{OPC-28} values of 0.95 and 1.0, respectively, to calculate the strength factors of PFA. These factors are calculated to be 0.41, 0.33 and 0.33 for mixes 37.5/37.5/25/0, 32.5/32.5/35/0 and 27.5/27.5/45/0, respectively. The average value (0.36) is used as the nominal strength factor for PFA in the presence of OPC, and is denoted SF_{PFA-28}.

Similar to the concretes formed from mixes containing CSAC/PFA binder blends, the compressive strengths at 28 days of the concrete cubes formed from mixes containing CSAC/GGBS binder blends (65/0/0/35 and 35/0/0/65) were substantially lower than those formed from mixes containing only CSAC or OPC binder. This was due to the absence of OPC, which prevented the secondary hydration of GGBS. However, unlike PFA, GGBS contributes to 28-day strength via its own hydration effect [8, 9]. The value of $SF_{CSAC-28}$ (0.95) and the 28-day strengths of the concretes formed from the two mixes 65/0/0/35 and 35/0/0/65 are used in Eq. 4.3 to calculate the nominal strength factor for GGBS in the absence of OPC ($SF_{GGBS-28}$), which is an average of 0.30.

Similarly, the 28-day strengths of concretes formed from 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 used in Eq. 4.3 to calculate the nominal strength factor of GGBS in the presence of OPC ($SF_{GGBS-28}$), the average of which is 0.60. As $Ca(OH)_2$, the hydration product of OPC, activates the secondary hydration of GGBS, the nominal strength factor of GGBS in the presence of OPC is higher than that of GGBS in absence of OPC, indicating the positive effect of OPC binder on the strength development of concrete that also contains GGBS binder. Thus, the nominal strength factors for PFA (SF_{PFA-28}) and GGBS ($SF_{GGBS-28}$) at 28 days are determined to be SF_{PFA-28} = -0.36 (without OPC) and 0.36 (with OPC); and $SF_{GGBS-28}$ = 0.30 (without OPC) and 0.60 (with OPC).

The determined strength factors at 28 days for all of the binders are entered into Eq. 4.3 and, provided that PFA and GGBS did not coexist in the binder combination, the equation for predicting the 28-day strengths of concretes containing CSAC/OPC/PFA and CSAC/OPC/GGBS binder blends becomes:

$$S_{CSAC-28} = (S_{OPC-28})[0.95(P_{CSAC}) + (P_{OPC}) + SF_{PFA/GGBS} - 28(P_{PFA/GGBS})] \quad \text{(Eq. 4.4)}$$

where, as stated above, SF_{PFA-28} is -0.36 (without OPC) or 0.36 (with OPC), and $SF_{GGBS-28}$ is 0.30 (without OPC) or 0.60 (with OPC).

The estimated 28-day strengths of the concretes that would be generated from the various mixes are summarised in Table 4.3, and are plotted against the measured 28-day strengths of these concretes in Figure 4.25. The relationship between the estimated strength and the measured strength is linear, with a coefficient of determination (R^2) of 0.9806. This indicates that the 28-day strength performance for a concrete formed from a mix containing CSAC blended with other binders can be predicted accurately using Eq. 4.3. It is well known that the strength development of concrete continues beyond the age of 28 days, especially in concretes containing supplementary binders such as PFA or GGBS. However, the trend of strength development largely depends on the combination of binders, and the strength performance of these binders varies after the age of 28 days due to the different mechanisms of their hydration processes [8 - 11]. This is of practical relevance because although a certain 28-day compressive strength is normally the compliance criterion for concrete quality, engineers are also interested in gauging the long-term strength development of concrete, as this contributes to improving safety factors in a structural design and is somewhat indicative of concrete durability.

4.5.3 Establishment of a predictive model for ultimate compressive strength

Although previous research has shown that the strength of concrete may continue to develop up to the age of 30 years under moist conditions, the strength at the age of 365 days is typically the maximum strength (aside from some exceptional cases) [24]. In this study, the 365-day compressive strength of concrete is therefore taken as its ultimate compressive strength.

As shown by the test results in Table 4.2, none of the concretes formed from mixes containing different percentage combinations of CSAC and OPC binders showed significant differences in their long-term strengths at 365 days, although the strength development trends at intermediate ages (7–365 days) varied. Similar to its performance at 28 days, pure CSAC concrete had a similar 365-day strength to that of pure OPC concrete. The 365-day compressive strengths of concretes formed from mixes containing various combinations of CSAC/OPC binders – 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) – were very similar to each other and to that of the concrete formed from pure OPC mix (0/100/0/0) (67.7 MPa). Thus, it appears that combinations of CSAC and OPC binders have similar effects on the long-term strength of a concrete up to 365 days as the individual binders alone.

Taking a similar approach to that used to calculate the 28-day strength factors of each binder, an equation is derived from these 365-day test results for concretes, based on the results of groups of mixes containing the same binder combinations. This involves considering the contribution of each binder to concrete strength and its own strength factor with respect to that of OPC at the same age.

The strength development at 365 days for concretes containing binder combinations of CSAC/OPC/PFA and CSAC/OPC/GGBS is derived from the following equation:

$$S_{CSAC/OPC/GGBS\text{-}365} = (S_{OPC\text{-}365})[(SF_{CSAC\text{-}365})(P_{CSAC}) + (P_{OPC}) + (SF_{PFA/GGBS\text{-}365})(P_{PFA/GGBS})] \qquad \text{(Eq. 4.5)}$$

By using the 365-day strength results of concretes formed from mixes 100/0/0/0, 75/25/0/0, 50/50/0/0 and 25/75/0/0 in Eq. 4.5, the average strength factor for CSAC at 365 days ($SF_{CSAC\text{-}365}$) is calculated to be 0.92, which is taken as the nominal strength factor of CSAC at 365 days.

The 365-day compressive strength results for the three concretes formed from mixes containing CSAC/PFA binder blends (75/0/25/0, 65/0/35/0 and 55/0/45/0) show that an increase in PFA content together with a reduction in CSAC content led to a significant strength reduction at 365 days (41.7, 32.3 and 25.8 MPa, respectively). As before, these results also show that PFA binder makes no contribution to strength development in the absence of OPC binder, and it also has a detrimental effect on strength development when blended only with CSAC binder. This is consistent with the 28-day performance of concretes formed from mixes containing CSAC/PFA binder blends, as mentioned earlier, and is also in agreement with the findings of Maring et al. [41], although those were only obtained up to an age of 90 days. By substituting the 365-day strength of the concretes formed from these three mixes (75/0/25/0, 65/0/35/0 and 55/0/45/0) into Eq. 4.5, the average strength factor for PFA binder in the absence of OPC is calculated to be -0.32. This value is used as the nominal strength factor for PFA binder at 365 days in the presence of CSAC and the absence of OPC ($SF_{PFA-365}$), and is the same as SF_{PFA-28}.

As mentioned, $Ca(OH)_2$ is the hydration product of OPC and reacts with PFA in a secondary hydration process that contributes to strength development [42]. Mixes 70/5/25/0 and 65/10/25 contain only 5% and 10% OPC binder, respectively, and thus the concentration of $Ca(OH)_2$ generated from the hydration of OPC would be relatively low, compared to that generated from other mixes containing greater proportions of OPC. Thus, the pozzolanic reaction of PFA in the concretes formed from these two mixes would be slower, thus reducing the speed of strength development. However, the compressive strengths of concretes formed from mixes 70/5/25/0 and 65/10/25 were equal to those of concretes formed from mixes of pure OPC and OPC/PFA binder blends at the age of 365 days. This proves that only a small amount of OPC is required to activate the secondary hydration of PFA, and that the rate of strength development is dependent on the concentration of $Ca(OH)_2$ generated by the OPC. Similarly, the compressive strengths of concretes formed from mixes 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, 64.1, 64.0, 64.4 and 65.5 MPa, respectively) are substituted into Eq. 4.5 to obtain an average strength factor for PFA of 0.95, which is used as the nominal strength factor for PFA in the presence of OPC.

Unlike the dependence of the performance of concretes containing PFA binder on the presence of OPC, GGBS binder contributed similarly to strength development for up to 365 days in concretes with and without OPC binder. By substituting the 365-day strength results of concretes formed from mixes containing CSAC/GGBS and CSAC/OPC/GGBS binder blends, namely mix 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), into Eq. 4.5, the average strength factor of GGBS ($SF_{GGBS-365}$) is calculated to be 0.77. This is used as the nominal strength factor of GGBS at 365 days, irrespective of the presence of OPC.

Similar to the prediction of the 28-day strengths of concretes formed from mixes containing various binder blends, an equation is developed to calculate the equivalent OPC content in concretes formed from mixes containing any combination of the four binders (CSAC, OPC, PFA and GGBS), in terms of long-term strength performance at the age of 365 days. By adding the strength factors at 365 days for all of the binders into the equation and assuming that PFA and GGBS do not coexist in the binder combination, the equation for concretes containing binder blends of CSAC/OPC/PFA and CSAC/OPC/GGBS becomes:

$$S_{CSAC\text{-}365} = (S_{OPC\text{-}365})[0.95(P_{CSAC}) + (P_{OPC}) + SF_{PFA/GGBS\text{-}365}(P_{PFA/GGBS})] \quad \text{(Eq. 4.6)}$$

where $SF_{PFA\text{-}365}$ is -0.32 (with OPC) or 0.95 (without OPC), and $SF_{GGBS\text{-}365}$ is 0.77 (with or without OPC).

Using Eq. 4.6, the estimated 365-day strengths of concretes formed from various mixes are calculated (Table 4.4) and plotted against the measured 365-day strengths of these concretes (Figure 4.26). The coefficient of determination (R^2) of 0.9672 confirmed that the predictions are reasonably accurate.

4.6 Conclusions and limitations

Based on the above findings, the following conclusions can be drawn.

(a) Concrete containing only CSAC binder exhibited very good early strength at only 2–6 h after mixing, and achieved similar strength levels at 28 days and later ages (up to 365 days) as those of concretes containing only OPC or combinations of OPC/PFA binders or OPC/GGBS binders.

(b) The equations (Eqs. 4.2, 4.3 and 4.4) developed for concretes containing CSAC incorporated with other binders can predict the compressive strength at various ages (2–6 h, 28 days and 365 days, respectively). The strength factors for different binders are derived for use in Eqs. 4.3 and 4.4 to predict the 28-day and 365-day strengths, respectively. The derived strength factors are:

(i) For 28-day strength predictions using Eq. 4.3:

$SF_{OPC\text{-}28}$ 1.00

$SF_{CSAC\text{-}28}$ 0.95

SF_{PFA-28} -0.36 (without OPC); 0.36 (with OPC)

$SF_{GGBS-28}$ 0.30 (without OPC)

0.60 (with OPC)

(ii) For 365-day strength prediction using Eq. 4.3:

$SF_{OPC-365}$ 1.00

$SF_{CSAC-365}$ 0.92

$SF_{PFA-365}$ -0.32 (without OPC); 0.95 (with OPC)

$SF_{GGBS-365}$ 0.77

(c) When PFA binder was blended with CSAC binder alone and in the absence of OPC binder, it exerted a detrimental effect on the strength development of the resulting concretes, up to the ages of 28 and 365 days. The reason for these reductions in strength at later ages is yet to be explored, and further study is recommended.

(d) Up to the age of 365 days, concretes formed from mixes incorporating PFA binder with only small quantities of OPC binder (e.g., 5% OPC in mix 70/5/25/0) were nevertheless able to fully utilise the hydraulic properties of the OPC binder to generate strength gains from PFA binder. Nevertheless, the results show that the smaller the quantity of OPC binder that is present, the slower the rate of strength development.

(e) GGBS binder makes its own contribution to strength development when blended with CSAC binder in the absence of OPC binder. In contrast, under the same conditions, PFA binder has a detrimental effect on strength development when blended with CSAC binder.

(f) In the presence of OPC binder, the addition of GGBS binder enhanced the strength development of concrete up to the age of 28 days to a greater extent than PFA binder. However, the reverse was true at the age of 365 days, even in the presence of only a small quantity of OPC binder.

(g) The equations derived in this study for predicting concrete strength are based on the results obtained from tests of 20 concrete mixes with the same binder content and water-to-binder ratio of 420 kg/m^3 and 0.45, respectively, which are commonly used parameters in the mix designs of grade 45 concretes. The applicability of the derived equations to concretes with other binder contents or water-to-binder ratios has yet to be verified. In addition, when binder materials are obtained from a source different to where they have been previously obtained, it is advisable to validate the derived equations again by conducting a mix trial, in which the measured compressive strengths of the resulting concrete are compared with the estimated values for the ages of (at least) a few hours and 28 days.

The results described in this chapter have been published in a paper entitled '1-year development trend of concrete compressive strength using calcium sulfoaluminate cement blended with OPC, PFA and GGBS' in *Construction and Building Materials*, 198 (2019), pp. 527–536 [44].

Table 4.1 Compressive strength results of concretes at different ages

Mix	2 h	4 h	6 h	1 day	7 days	14 days	28 days	90 days	180 days	365 days
	Compressive strength (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: ‘--’ denotes that the concrete was insufficiently strong for testing.

Table 4.2 Early strength results of partial and pure CSAC concretes

Mix	proportion of CSAC	Early strength results (MPa)				Average % of early strength compared to that of pure CSAC concrete
		2 h	4 h	6 h	Average	
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 4.3 Measured 28-day strengths vs estimated 28-day strengths of concretes, based on strength factors of various binders

Mix IDs	% 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 wrt 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 4.4 Measured 365-day strengths vs estimated 365-day strengths of concretes, based on the strength factors of various binders

Mix IDs	% of Binder Content and Their Strength Factors at 365-day of: $SF_{CSAC-28} = 0.92$; $SF_{OPC-28} = 1.00$; $SF_{PFA-28} = -0.32$, (without OPC); $SF_{PFA-28} = 0.95$ (with OPC); $SF_{GGBS-28} = 0.77$				Combined Strength Factor wrt 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

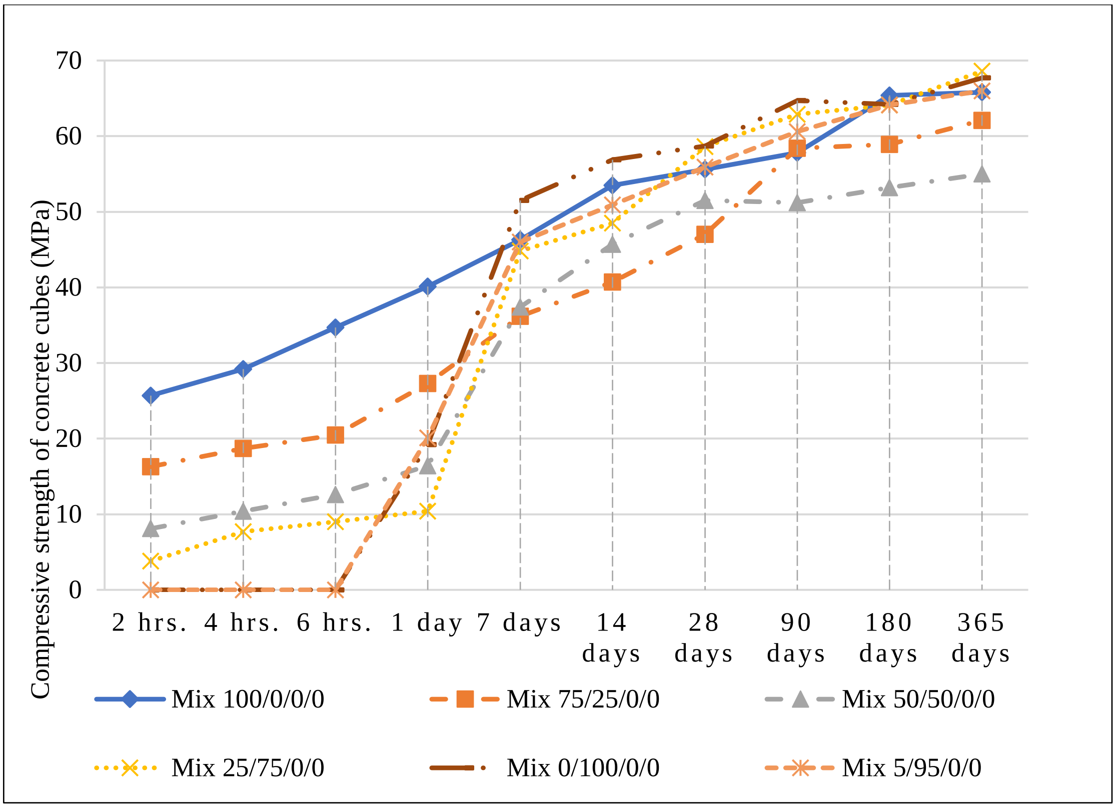

Figure 4.1 Strength development trends of CSAC/OPC concretes

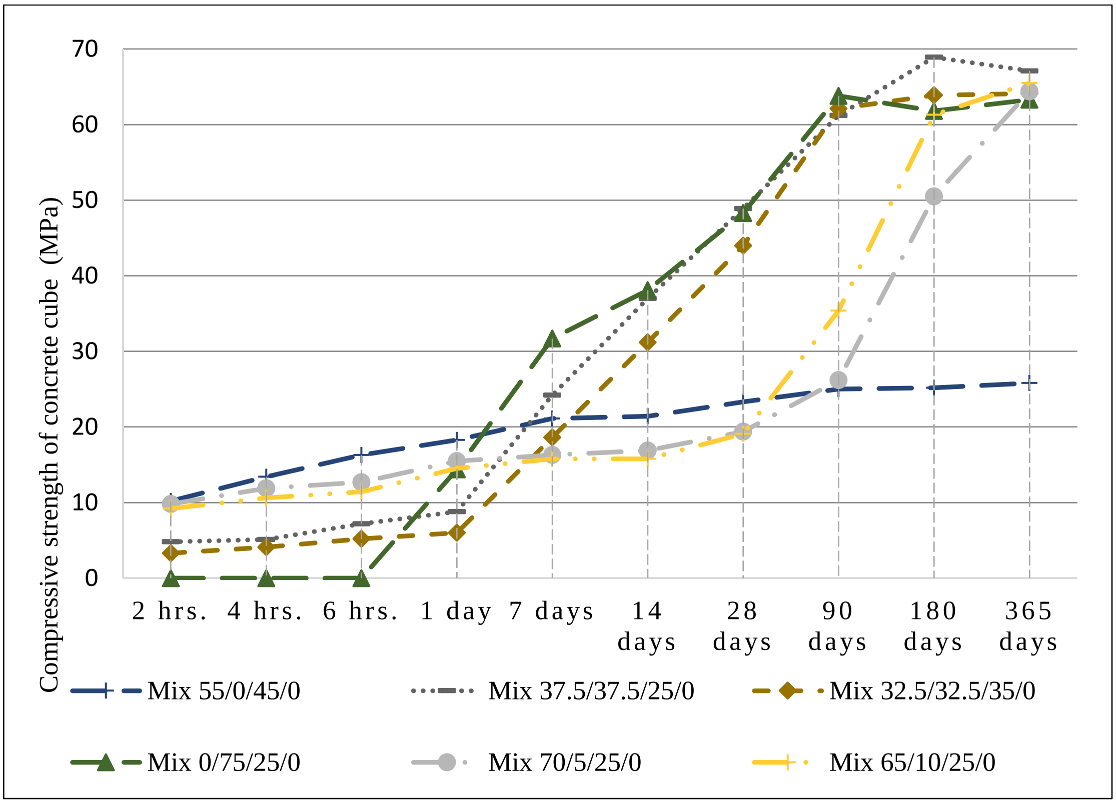

Figure 4.2 Strength development trends of CSAC/OPC/PFA concretes

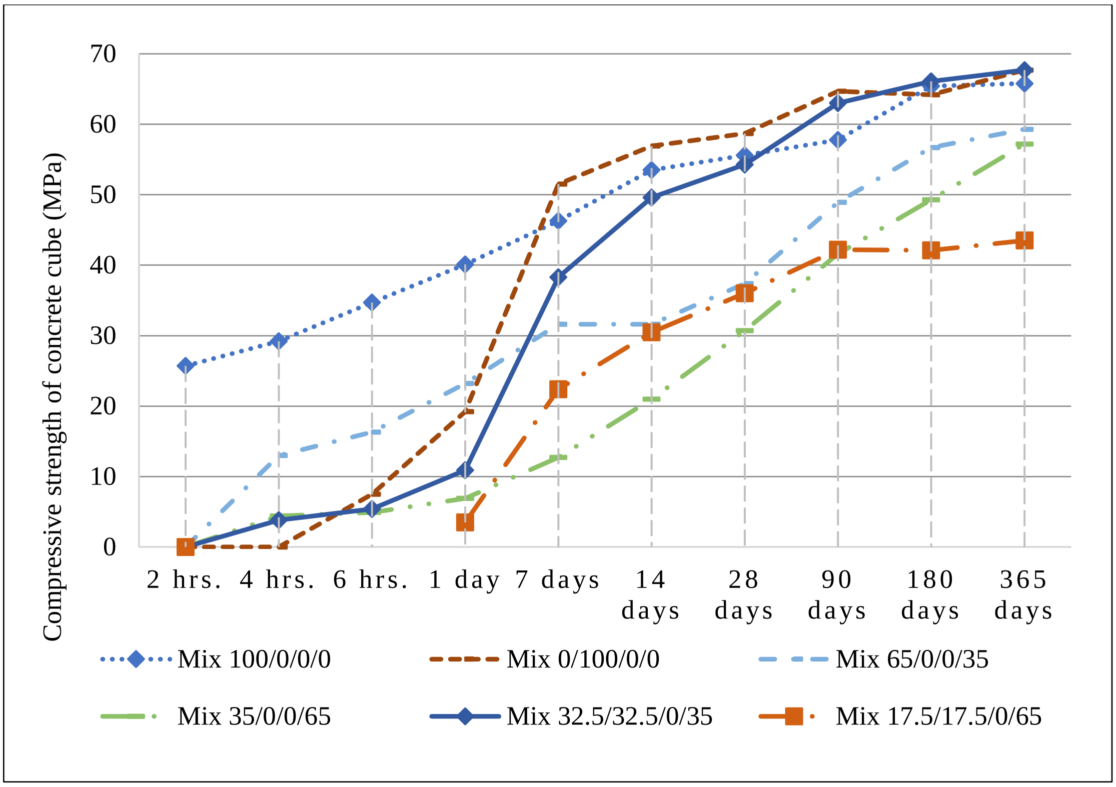

Figure 4.3 Strength development trends of CSAC/OPC/GGBS concretes

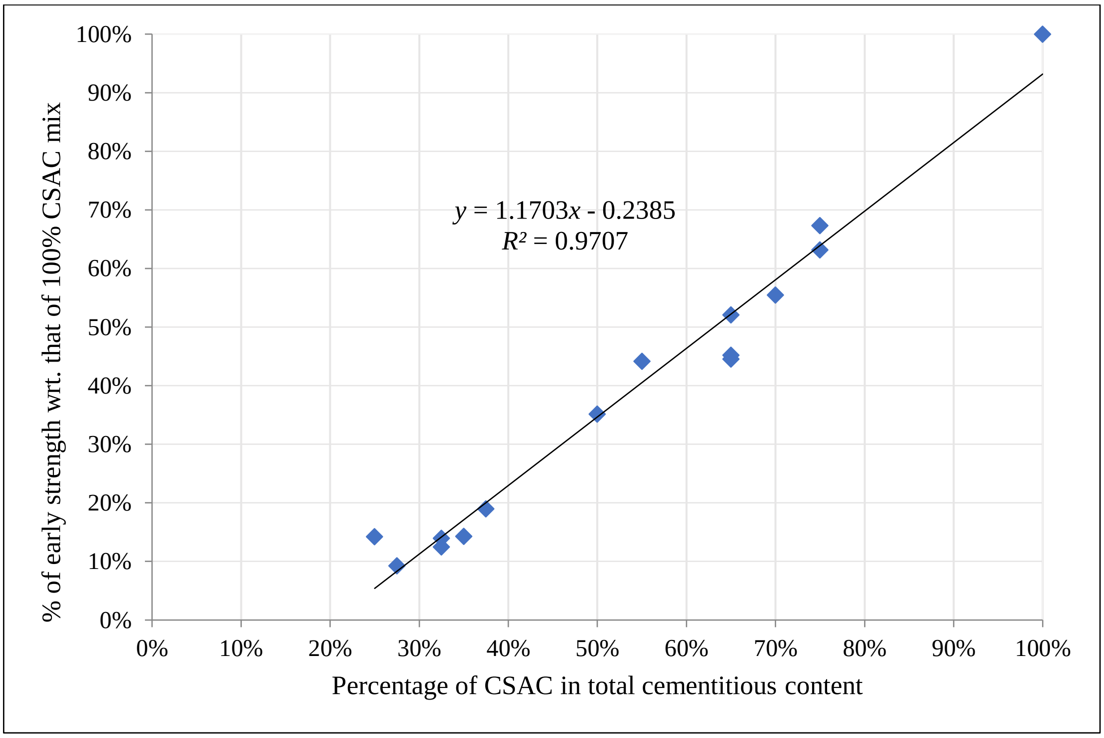

Figure 4.4 Relationship between the percentage of CSAC in a binder combination of a concrete and its early strength performance vs that of 100% CSAC concrete

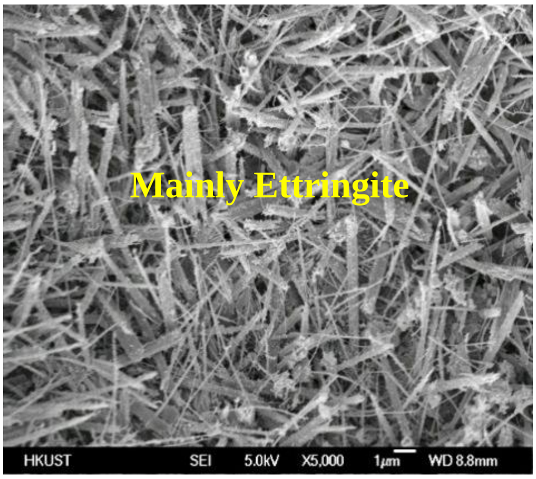

Figure 4.5: SEM photograph 100/0/0/0

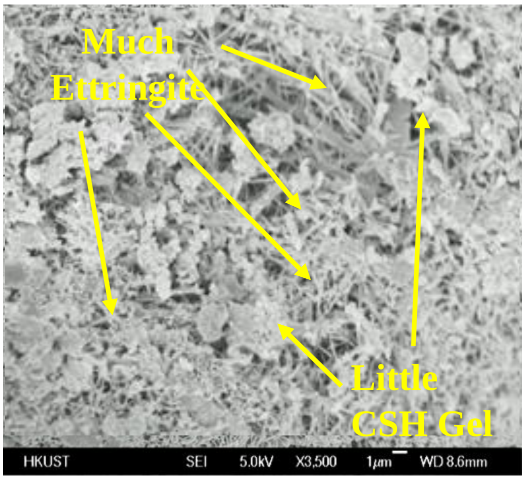

Figure 4.6: SEM photograph 75/25/0/0

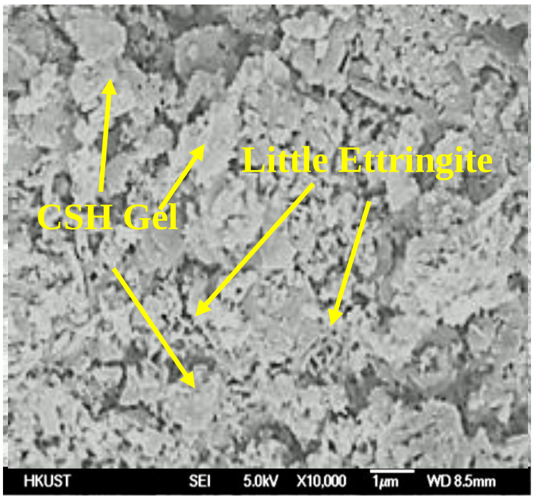

Figure 4.7: SEM photograph 50/50/0/0

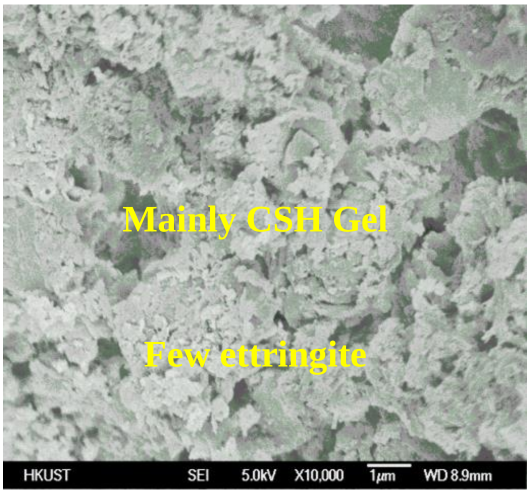

Figure 4.8: SEM photograph 25/75/0/0

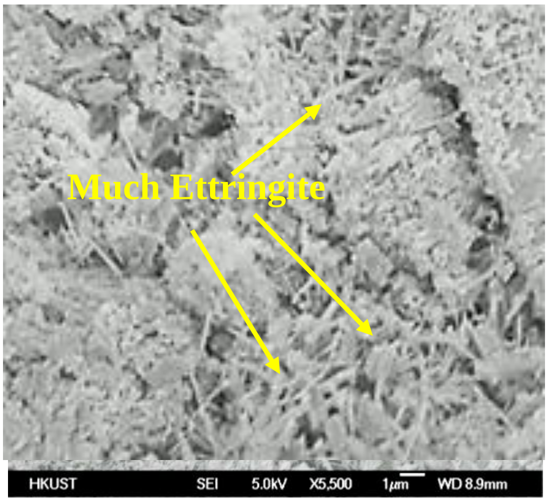

Figure 4.9: SEM photograph 75/0/25/0

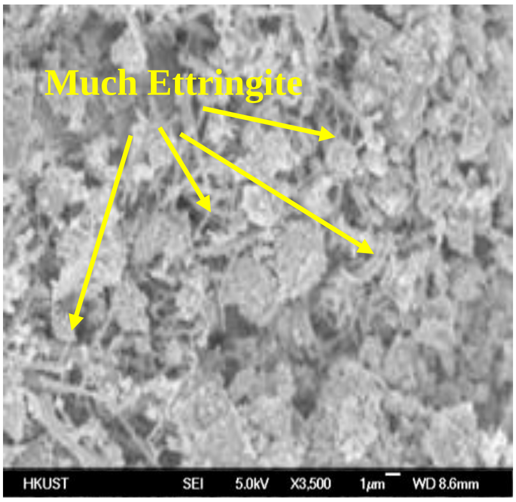

Figure 4.10: SEM photograph 65/0/35/0

Figure 4.11: SEM Photograph 55/0/45/0

Figure 4.12: SEM photograph 0/100/0/0

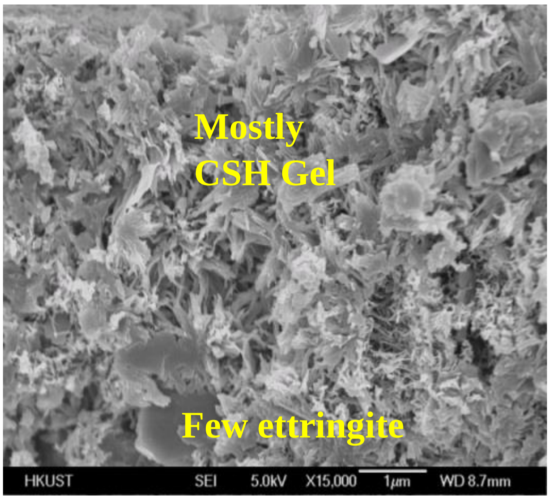

Figure 4.13: SEM photograph 37.5/37.5/25/0

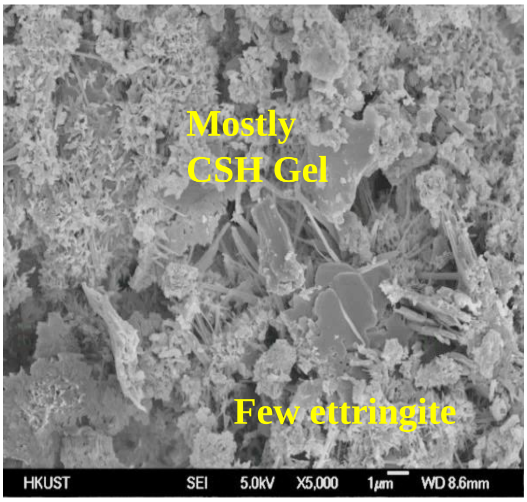

Figure 4.14: SEM photograph 32.5/32.5/35/0

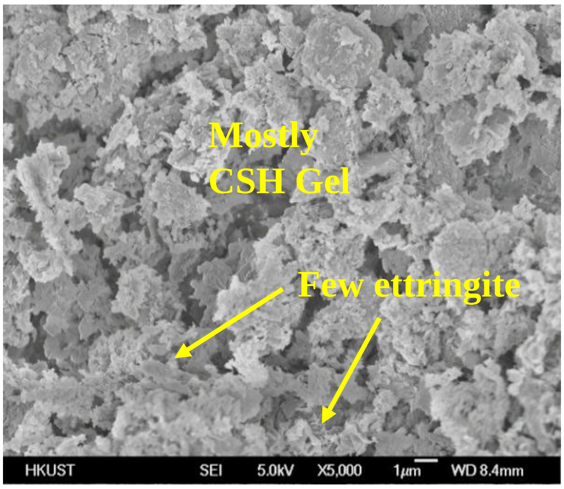

Figure 4.15: SEM photograph 27.5/27.5/45/0

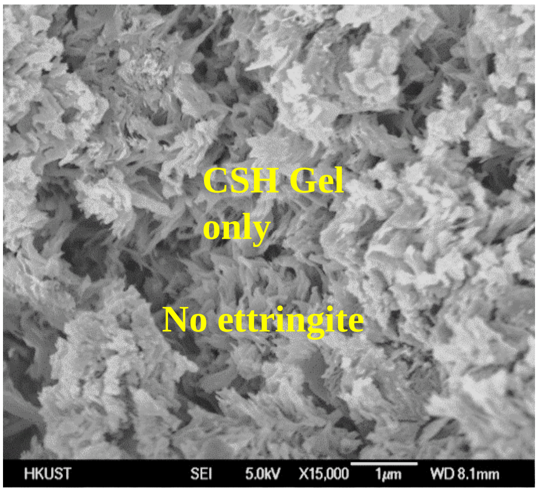

Figure 4.16: SEM photograph 0/75/25/0

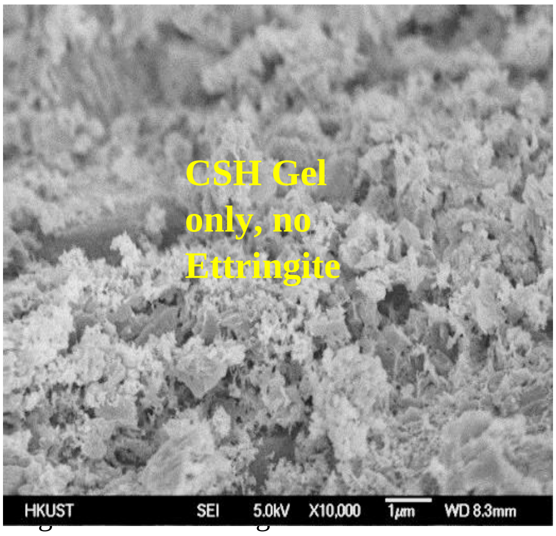

Figure 4.17: SEM photograph 0/65/35/0

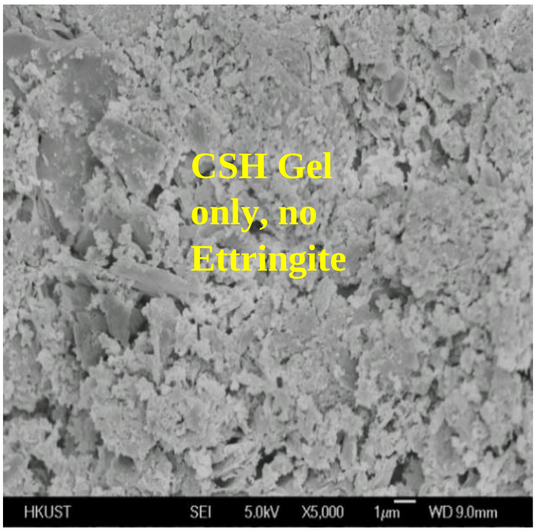

Figure 4.18: SEM photograph 5/95/0/0

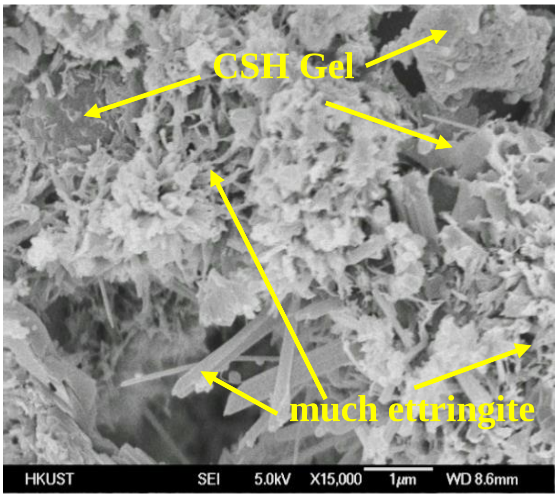

Figure 4.19: SEM photograph 70/5/25/0

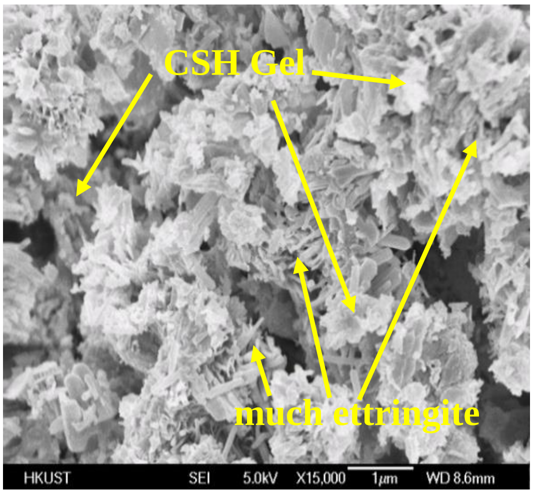

Figure 4.20: SEM photograph 65/10/25/0

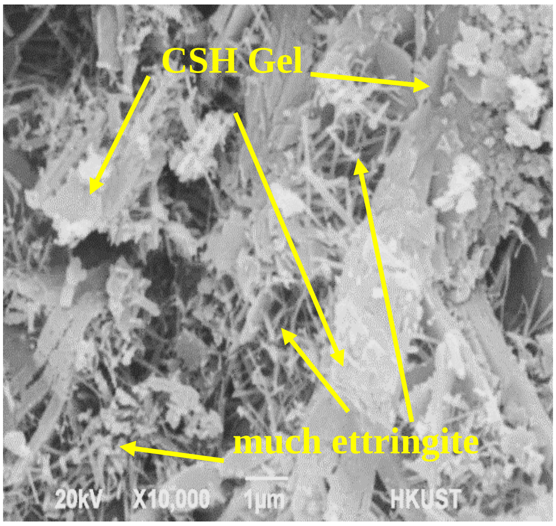

Figure 4.21: SEM photograph 65/0/0/35

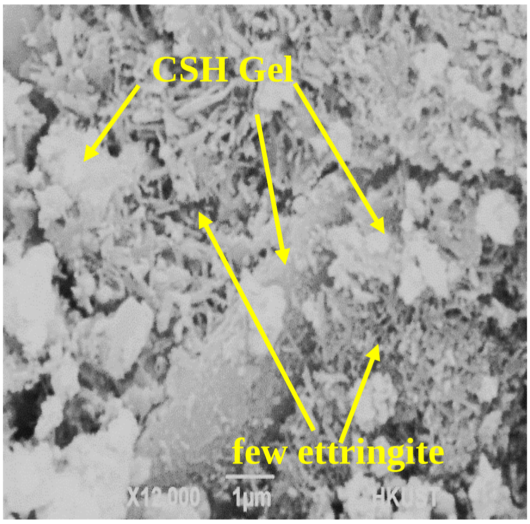

Figure 4.22: SEM photograph 35/0/0/65

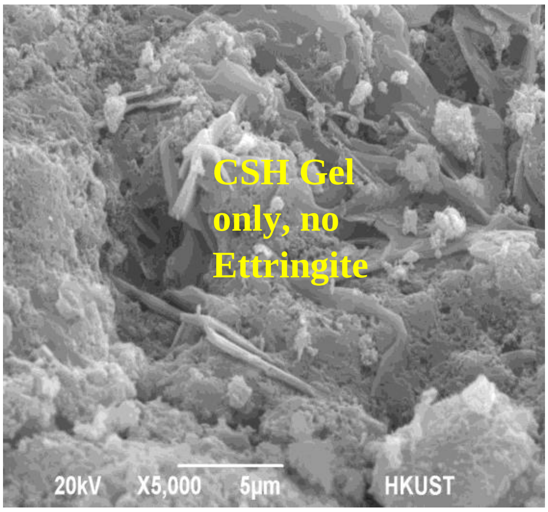

Figure 4.23: SEM photograph 32.5/32.5/0/35

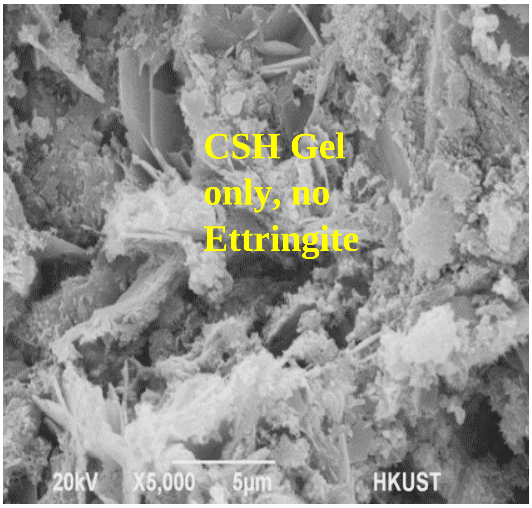

Figure 4.24: SEM photograph 17.5/17.5/0/65

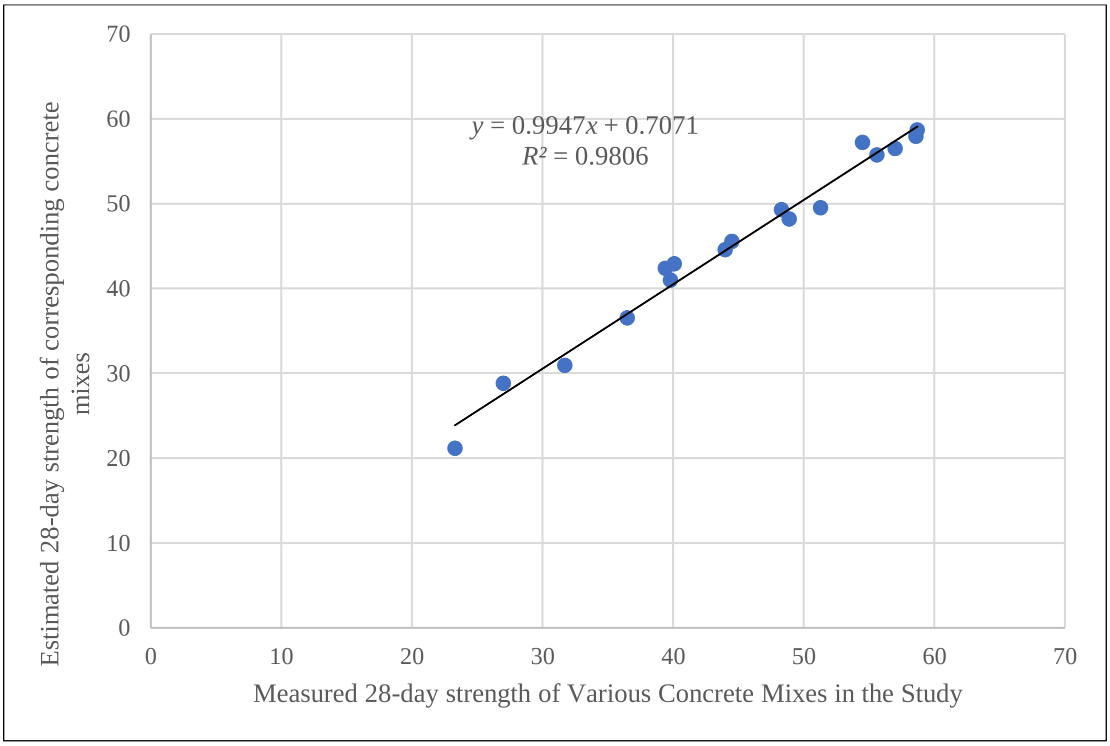

Figure 4.25 Measured 28-day strength vs 28-day strength estimated using an equation containing the nominal strength factors of binders

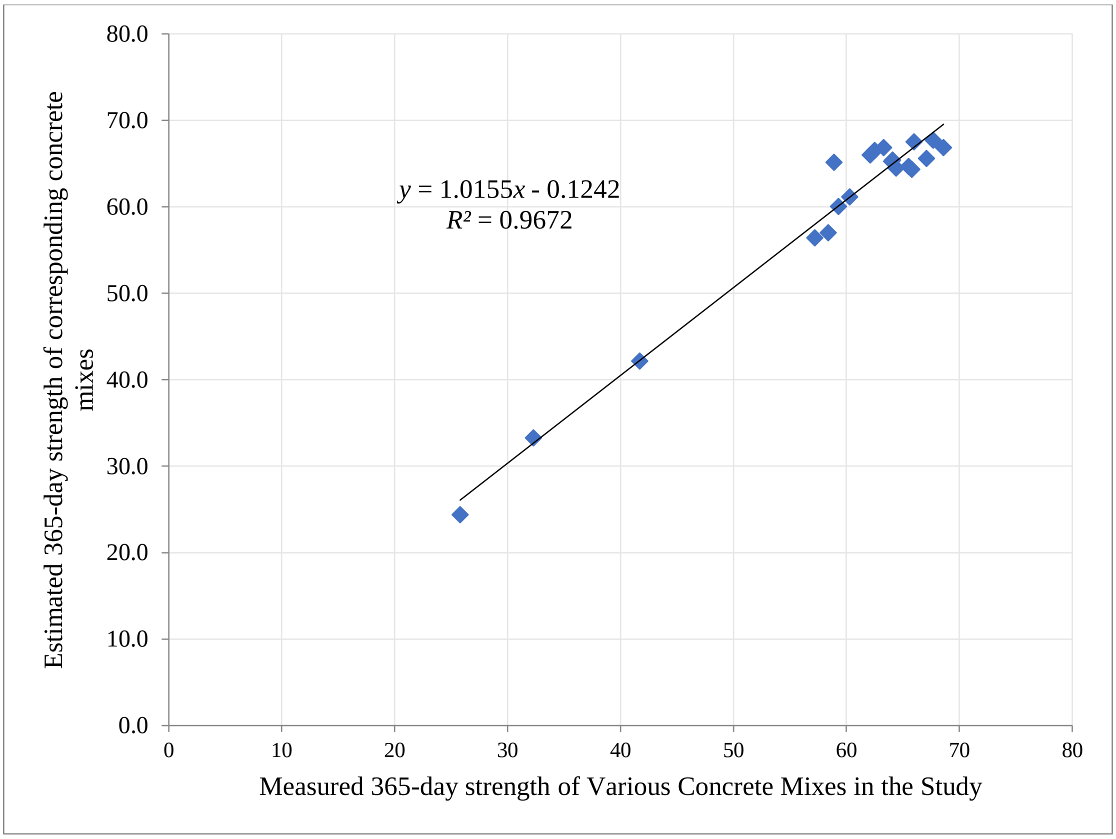

Figure 4.26 Measured 365-day strength vs 365-day strength estimated using an equation containing the nominal strength factors of binders

Chapter 5 Predictive Model for Ultimate Shrinkage Development of Concretes containing Combinations of CSAC, OPC, PFA and GGBS Binders

5.1 Introduction

In cementitious materials such as concrete, total shrinkage comprises autogenous shrinkage and drying shrinkage [18]. Autogenous shrinkage results from the consumption of moisture during the hydration process of cementitious materials, whereas drying shrinkage results from the loss of moisture to the atmosphere from the concrete itself, when it is subject to ambient temperature and humidity conditions [18]. In this regard, the magnitude and developmental trend of autogenous shrinkage is dependent on the hydration process of the individual and mixed cementitious materials, which also determines the strength development trend of concrete. The occurrence of the two shrinkage mechanisms in a concrete, which is represented by the ratio of autogenous shrinkage to drying shrinkage, depends on its water-to-binder ratio. The lower the binder ratio, the greater the proportion of autogenous shrinkage, as there is less free water in the total mixing water that can escape to the atmosphere, other than the portion consumed in hydration. Therefore, autogenous shrinkage also warrants examination when studying the strength development trend of a concrete formed from a certain mix.

In the GL2000 model used in this study, the prediction of shrinkage performance is based on the 28-day compressive strength of concrete. As the formula given in the model does not apply to concretes with cement types other than OPC types I, II and III as classified in ASTM C150-07 (“Standard Specification for Portland Cement”) [19], the K factors for concretes containing the binder combinations examined in this study are developed based on the shrinkage measurements. Thus, the applicability of the GL2000 model for OPC concrete is first verified, and then the shrinkage measurements of concretes containing other binders are used to develop the K factors for these concretes. Finally, the developed K factors are verified by estimating the shrinkage and ultimate shrinkage of each concrete.

Shrinkage development typically continues for years, with the rate of shrinkage gradually decreasing until it finally ceases or reaches an equilibrium with the environment. In addition, the volume stability of CSAC binder is well known, and results from the early formation of ettringite crystals, which tend to expand and thereby compensate for subsequent drying shrinkage [18]. Nevertheless, commonly used shrinkage-testing methods only collect measurements up to the age of 28 or 56 days [17]. Furthermore, incorrect estimates of the ultimate shrinkage performance of a concrete may also be made if its shrinkage development has been delayed, rather than permanently reduced. In this case, shrinkage may continue to develop and ultimately reach the same or similar magnitude as that of an ordinary concrete that does not contain CSAC binder.

In a previous paper by the author [44], concretes containing various combinations of CSAC, OPC, PFA and GGBS binders are shown to exhibit different strength development trends, due to interactions between binders that alter their respective hydration mechanisms. It was also proven in this study [44] that the hydration mechanisms of PFA and GGBS binders vary depending on whether OPC is also present. As such, the autogenous shrinkage development trends of concretes are likely to be sensitive to the hydration mechanisms of the binders they contain. The strength development trends of the concretes examined in this previous study [44] are therefore also reviewed in this study to analyse their respective shrinkage development trends.

As concrete shrinkage is an important parameter in structural engineering design, design codes such as ACI 318R-14 ("Building code requirements for structural concrete – Commentary on building code requirements for structural concrete") [12] and BS EN 1992-1-1:2004+A1:2014 ("Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings") [13] stipulate that the long-term shrinkage of concretes must be predicted at the structural design stage. However, shrinkage prediction models in current design codes are applicable only to concretes containing ordinary binder materials, not to those containing binders such as CSAC and its combinations with OPC, PFA or GGBS. For example, ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], which is referred to in ACI 318R-14 ("Building code requirements for structural concrete – Commentary on building code requirements for structural concrete") [12], is stated as being applicable only to predicting the shrinkage of concretes containing OPC, sulphate-resistant cement or rapid-hardening cement binders. Hence, the shrinkage of concretes containing CSAC and its combinations with other binders cannot be estimated using the prediction model given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. There is therefore a need for shrinkage prediction models for concretes containing these binders. Accordingly, a prediction approach based on the GL2000 model, as described in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], is used in this study.

5.2 Research significance

Concrete shrinkage is defined as the decrease in the dimensions of a concrete member due to a loss of moisture by consumption in a hydration process (autogenous shrinkage) and evaporation to the atmosphere of the surrounding environment (drying shrinkage). It is a key parameter of concrete that may have detrimental effects on the long-term durability of a concrete member, such as by inducing the formation of cracks. Thus, as part of design considerations, structural engineers must take into account the potential extent of shrinkage that may occur in concrete, and deploy measures to prevent or limit the possible consequences (e.g., shrinkage-induced cracks). Shrinkage estimates must also be made to calculate the loss of prestress in prestressed concrete, which is essential for its design.

In most design codes and many renowned technical papers, equations or predictive models are provided for engineers to use to estimate shrinkage in concretes. However, these shrinkage prediction models have been developed for concretes containing ordinary binders (e.g., OPC), and it is uncertain whether they are applicable to estimating shrinkage in concretes incorporating CSAC or its combinations with OPC, PFA and GGBS binders. There is therefore a need for a suitable predictive model for shrinkage that is applicable to concretes that contain a wider range of commonly used binder combinations.

Accordingly, this part of the study derives appropriate calculation factors for use in a model to predict the shrinkage performance of concretes containing various combinations of CSAC and other binders, which have not previously been determined.

K factors for combinations of CSAC, OPC, PFA and GGBS binders are required to enable reasonably accurate predictions of the shrinkage performance of concretes that contain these binders, to facilitate structural engineering design.

5.3 Methodology

Based on the test regime and methodology described in Chapter 3, the shrinkages of concretes formed from various mixes were measured up to the age of 365 days. At this age, the shrinkage development trends due to interactions between binder materials are expected to be sufficiently stable to be suitable for use in calculating ultimate shrinkage values.

In ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], several models are given for estimating the shrinkage performance of concrete. In this study, the widely adopted GL2000 model is used to generate shrinkage estimates that are compared with the ultimate shrinkage values calculated from the measured 365-day shrinkage values. For the GL2000 model, K factors for the shrinkage performance characteristics of binders are given only for OPC types I, II and III as classified in ASTM C150-07 ('Standard Specification for Portland Cement') [19], namely OPC, moderate sulphate-resistant cement and high early-strength cement, respectively. It is explicitly stated in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15] that the models given were developed for concretes containing typical compositions of the specified binders and that further model calibration must be performed by testing concretes containing other binder compositions.

Thus, new K factors were established in this study and used in the GL2000 model to predict the ultimate shrinkage values of concretes, and these were compared with the ultimate shrinkage values calculated from measurements of these concretes. Deviations between the predicted and calculated values within ±20%, which is the acceptable range suggested in ACI 209.2R-08 (“Guide for modelling and calculating shrinkage and creep in hardened concrete”) [15], confirm that the established K factors give predicted shrinkage values that are adequately close to the ultimate shrinkage values based on measurements. The predicted and calculated shrinkage values for all of the 20 concrete mixes are then plotted on a linear graph to evaluate the replicability of the derived predictive model in terms of the coefficient of determination.

5.4 Test results and discussions

The shrinkage results are summarised in Tables 5.1 to 5.4, which comprise the results for concretes containing the binder combinations CSAC/OPC, CSAC/PFA, CSAC/OPC/PFA and CSAC/OPC/GGBS, respectively. These results are also plotted in Figures 5.1 to 5.4 to illustrate the shrinkage development trends of the four combinations of binders. The 28-day compressive strength results obtained from concrete cube specimens, as discussed in Section 4, are converted to 28-day cylinder strength results (Table 5.5) for use in the GL2000 model. The K factors for each binder are derived for use in the GL2000 model. The combined K factors, representing the combined effects of certain binder combinations, are also calculated. These are then used to calculate the predicted ultimate shrinkage values of concretes formed from mixes containing these binder combinations. The predicted ultimate shrinkage values of all concrete mixes are then compared with the ultimate shrinkage values calculated from the measured 365-day shrinkage values using Eq. 5.3, which is derived from Eq. A1 in ACI 209.02R-08 (“Guide for modelling and calculating shrinkage and creep in hardened concrete”) [15].

The results are tabulated in Table 5.5. The ultimate shrinkage values calculated by using the derived K factors, or combined K factors, in the GL2000 model are plotted in Figure 5.5 against the ultimate shrinkage values calculated from the measured 365-day shrinkage measurements. The derived K factors are verified by the degree of correlation of the curve in Figure 5.5. Further validation of the K factors and the applicability of the GL2000 model is obtained by using

Equation A1 (given in ACI 209.02R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]) to calculate the estimated shrinkage values of all of the concrete mixes at ages of 2, 7, 28, 56, 90, 180 and 365 days, which are then compared with the corresponding measured shrinkage values. The comparison results are summarised in Table 5.6, and the calculated estimated shrinkage values at different ages are plotted against the corresponding measured values for each concrete/concrete mix in Figures 5.6 to 5.25. The coefficients of determinations of all of the correlation curves are evaluated to confirm the validity of the derived K factors and the applicability of the GL2000 model as a predictive model for shrinkage.

As shown in Figures 5.1 to 5.4, concretes containing different binder combinations had relatively stable and similar measured shrinkage values at the age of 365 days, and exhibited slow rates of shrinkage development. Eq. A-1 from ACI 209.02R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], denoted as Eq. 5.1 below, is used to correlate the shrinkage strain at 365 days with the ultimate shrinkage strain.

$$\varepsilon_{t} = \varepsilon_{shu} \frac{(t-tc)^{\alpha}}{f+(t-tc)^{\alpha}} \qquad \text{(Eq. 5.1)}$$

where t_c is the age (in days) when the initial dimensional measurement of the specimen is taken. In this study, t_c equalled 1 day, as the specimens started to dry on the day after casting. t is an interim age (in days) that is used to estimate the shrinkage value at that age; f (in days) and α are constants for a member of a given shape and size that relate shrinkage strains with time as defined in ACI 290.2R-08 [15]. f is calculated using Equation A3 from ACI 290.2R-08 [15], ("Guide for modelling and calculating shrinkage and creep in hardened concrete") denoted as Eq. 5.2 below, and α is equal to 1, as recommended in the same ACI report [15].

$$f = 26.0e^{1.42(0.01)(V/S)} \qquad \text{(Eq. 5.2)}$$

where V/S is the volume–surface ratio of the test specimen, in mm.

The volume and surface area of the 75-mm × 75-mm × 285-mm prism test specimens used in this study were 1,603,125 mm^3 and 96,750 mm^2, respectively. The V/S was therefore 16.57 mm.

Therefore, $f = 26.0e^{1.42(0.01)(V/S)} = 26.0e^{1.42(0.01)(16.57)} = 33$, and by substituting the values of $f = 33$, $t = 365$, $t_c = 1$ and $\alpha = 1$ into Eq. 5.1,

$$\varepsilon_{sh\text{-}365} = 0.92\varepsilon_{shu} \qquad \text{(Eq. 5.3)}$$

5.5 Establishment of predictive models for the ultimate shrinkage values of concretes containing combinations of CSAC, OPC, PFA and GGBS binders

5.5.1 CSAC/OPC binder blends

The CSAC/OPC concretes for study were formed from mixes 100/0/0/0, 75/25/0/0, 50/50/0/0, 25/75/0/0, 5/95/0/0 and 0/100/0/0, and their shrinkage measurements are given in Table 5.1 and plotted in Figure 5.1. The shrinkage performance of the concrete formed from the mix containing only OPC, the most commonly used binder, is used as the datum reference for comparing concrete mixes of other binder combinations and to verify the applicability of the GL2000 model. The concrete formed from the pure OPC mix (0/100/0/0) exhibited a net shrinkage at the initial stage of the hydration process that continued to develop until 56 days, at which time the shrinkage development slowed, resulting in the shrinkage value of 687 microstrains (με) at 365 days (as shown in Table 5.1).

Ye'elimite ($Ca_4Al_6O_{12}SO_4$) in CSAC reacts with $CaSO_4$ during its hydration process to form crystalline ettringite ($Ca_6Al_2(SO_4)_3(OH).26H_2O$). The crystallisation of ettringite in the initial hydration of CSAC leads to rapid strength gains and the early expansion of concretes containing this binder [7, 44, 45]. The shrinkage measurement results of the pure CSAC concrete formed from mix 100/0/0/0 exhibited a peak expansion at the age of 2 days (+256 με), due to the effect of early ettringite formation in CSAC [7, 45]. Shrinkage occurred at the same time, but was masked by the greater magnitude of ettringite crystal expansion, resulting in the net expansion of the concrete at this age. This was consistent with the previous findings of Yang [7] and Bizzozero et al. [45], who indicated that the expansion of ettringite crystals generated in a pure CSAC concrete matrix is most apparent during the first day after casting.

Following the cessation of early ettringite formation, the results reveal negative growth in the net dimensional change of pure CSAC concrete, due to the continuous shrinkage development and decaying expansion. A nearly balanced dimensional change was reached at the age of 28 days (+28 με). Net shrinkage values were recorded at 56 days (-18 με), 90 days (-35 με), 180 days (-148 με) and 365 days (-190 με), and these magnitudes are considered to indicate good dimensional stability. The results therefore confirm that CSAC imparts long-term dimensional stability to concrete. To estimate the notable ultimate shrinkage strain, ε_{shu}, Equation A-99 from ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15] is used, denoted below as Eq. 5.4:

$$\varepsilon_{shu} = 900K\left(\frac{30}{fcm_{28}}\right)^{1/2} \mu\varepsilon \qquad \text{(Eq. 5.4)}$$

where K is the constant for a specific binder, denoted as K_X for binder X. Thus, K_{OPC} is the shrinkage constant for OPC (Type I in ASTM C150-07 ("Standard Specification for Portland Cement") [19]), and $K_{OPC} = 1$ is used in this study, as given in Table A.14 of the ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. Additionally, fcm_{28} is the mean compressive cylinder strength of the concrete (MPa). As indicated in Table 5.5, the concrete cube compressive strength at 28 days was 58.7 MPa, and thus by using the commonly adopted correlation factor between the cylinder and cube compressive strengths of 0.8, fcm_{28} = 58.7 × 0.8 = 47.0 MPa.

By substituting the values of K_{OPC} (i.e., 1) and fcm_{28} into Eq. 5.4, the ultimate shrinkage strain (ε_{shu}) is calculated to be 719 με. Based on Eq. 5.3, the ultimate shrinkage strain is calculated by dividing the shrinkage value measured at 365 days with the correction factor of 0.92, i.e., 687 με ÷ 0.92 = 747 με, which agrees well with the value calculated using the GL2000 model (719 με) and a predicted-to-calculated shrinkage value ratio of 1.0. In ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], it is stated that results from predictive models must be within ±20% of the test data for shrinkage (i.e., the ratio of test data to the predicted values for ultimate shrinkage strain must fall between 0.8 and 1.2). The good agreement of the ultimate shrinkage value calculated from the measured 365-day shrinkage value with the ultimate shrinkage predicted using a K_{OPC} of 1.0 verifies the applicability of the GL2000 model for processing the test results obtained in this study.

The measured long-term shrinkage value of pure CSAC concrete (formed from mix 100/0/0/0) at 365 days was 190 με. Based on this measured result, a test figure of 0.29 is set for the K value for CSAC (K_{CSAC}) in the equation given in GL2000 model for calculating ε_{shu}. By using Eq. 5.4, a 28-day cube strength of 55.6 MPa for pure CSAC concrete (Table 4.2) and a corresponding cylinder strength of 55.6 MPa × 0.8 = 44.5 MPa, the predicted ultimate shrinkage value is calculated as:

$$\varepsilon_{shu} = 900 \times (0.29) \times \left(\frac{30}{44.5}\right)^{1/2} = 214\ \mu\varepsilon$$

which is also close to the ultimate shrinkage strain obtained by dividing by the measured 365-day shrinkage for the concrete formed from the pure CSAC mix, i.e., 190 με ÷ 0.92 = 207 με, and the estimated shrinkage value ratio is 1.0 (Table 5.5). This is also within the acceptable range of ±20% as stated in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], and thus verifies the assumed K factor for CSAC (K_{CSAC}) in pure CSAC concrete (0.29).

The partial replacement of CSAC with OPC in mixes 75/25/0/0, 50/50/0/0/, 25/75/0/0 and 5/95/0/0 led to concretes in which a net shrinkage occurred much earlier (at 7 days) than that in concrete formed from a pure CSAC mix (100/0/0/0). The shrinkage in these concretes developed to different levels at 365 days depending on the CSAC content, with the long-term shrinkage value increasing as the CSAC content decreased, as shown in Table 5.1. In contrast, as given in the strength results in Table 4.2, the early strengths at day 1 of concretes formed from the mixes containing CSAC/OPC binder blends decreased as CSAC decreased.

Both phenomena are attributable to a reduction in the formation of ettringite, whose expansion helps to increase strength and compensate for shrinkage, as discussed in Section 4 and the author's published paper [44]. This reduction appears to result from the consumption of $CaSO_4$ in CSAC by OPC during the hydration process of the CSAC/OPC binder matrix, i.e., $CaSO_4$ is consumed in a reaction with OPC before it can react with CSAC [44]. The combined effect of the reduction in CSAC content in the binder combination and the prevention of CSAC hydration by OPC is a decrease in early ettringite formation. This also leads to less expansion and thus less compensation for shrinkage, which results in greater magnitudes of shrinkage at both early and long-term ages. Consequently, the benefits of the rapid strength gain and reduced shrinkage properties of concretes that contain CSAC binder are diminished when CSAC is partially replaced by OPC in a binder combination.

The comparison of the long-term shrinkage performance of concrete containing CSAC/OPC binder combinations with that of pure CSAC concrete reveals that the shrinkage-reducing effect of CSAC appears to be weakened by the presence of OPC. The combined K factor of binders in concretes formed from mixes containing CSAC/OPC binder blends is dependent on both K_{CSAC} and $K_{OPC,}$ the values of which are in proportion to their percentages (P) in the binder combination (i.e., $K_{CSAC/OPC} = K_{CSAC} \times P_{CSAC} + K_{OPC} \times P_{OPC}$). Thus, by using Eq. 5.4 with the assumed values of $K_{CSAC} = 0.29$ and $K_{OPC} = 1.0$ and the percentages of CSAC and OPC in the binder combinations of mixes 75/25/0/0, 50/50/0/0, and 25/75/0/0, the predicted ultimate shrinkage values of the corresponding concretes are calculated to be 351, 474 and 590 με, respectively. These are in reasonable agreement with the ultimate shrinkage values calculated by dividing the measured 365-day results of these concretes by the conversion factor of 0.92, which are 428, 618 and 773 με. In addition, the ratios of the predicted-to-calculated shrinkage values are all 0.8. All of these data are within the acceptable range of ±20%, as given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. The results are listed in Table 5.5.

5.5.2 CSAC/PFA and CSAC/GGBS blends

The effects of CSAC/PFA binder blends are studied by examining the shrinkage behaviour of concretes formed from mixes 100/0/0/0, 75/0/25/0, 65/0/35/0, 55/0/45/0 and 0/100/0/0; their shrinkage measurement results are listed in Table 5.3 and their shrinkage developmental trends are plotted in Figure 5.2. The pozzolanic reaction of PFA (which is also termed secondary hydration) must be induced by $Ca(OH)_2$ in the concrete matrix, and $Ca(OH)_2$ is the hydration product of OPC [24, 41]. Thus, if OPC is absent from the CSAC/PFA matrix, no $Ca(OH)_2$ is generated, and thus the pH required to activate the pozzolanic reaction of PFA is not reached; consequently, PFA binder does not contribute to strength development via its pozzolanic pathway [24, 41].

In related research, Maring et al. [41] observed that pore solutions of CSAC matrix generally have a much lower pH than those of OPC matrix, as $Ca(OH)_2$ is not formed in the hydration process of the latter. This phenomenon was confirmed by the results of isothermal calorimetry in the same study [41], and showed that little or no hydration of PFA occurred due to the absence of $Ca(OH)_2$. The results obtained in Section 4 and the author's previous study [44] agree with the above findings in [41], showing that PFA binder makes no contribution to the strength development of concretes when blended with CSAC binder only, as CSAC does not produce $Ca(OH)_2$ in its hydration process. Consequently, when the hydration of PFA binder is not activated, it triggers little or no autogenous shrinkage and largely induces only drying shrinkage.

Bescher [46] found that a novel self-organised structure of micron-sized (20–100 μm) acicular crystals extending outwards from the "vertebrae" of PFA was formed in the hydration process that occurred in the CSAC/PFA binder blend matrices. However, the effect of this novel structure on the properties of CSAC/PFA concrete, such as its strength and shrinkage development, has yet to be studied. The shrinkage results obtained in this study for concretes formed from mixes containing combinations of CSAC/PFA binder (mixes 75/0/25/0 and

65/0/35/0) show that these concretes exhibited similar shrinkage trends to that of pure CSAC concrete. This indicates that the novel self-organised structure in the blended mix does not influence shrinkage development in a CSAC/PFA concrete.

The K factor for PFA in the absence of OPC (K_{PFA}) is assumed to be 0.05 for the purposes of data analysis. The combined K factor ($K_{CSAC/PFA}$) is regarded as the sum of K_{CSAC} and K_{PFA} with respect to the percentage of CSAC and PFA in the binder combination, and thus $K_{CSAC/PFA} = K_{CSAC} \times P_{CSAC} + K_{PFA} \times P_{PFA}$. Then, by using the corresponding 28-day cylinder strengths and values for $K_{CSAC/PFA}$ for mixes 75/0/25/0, 65/0/35/0 and 55/0/45/0 in Eq. 5.4, the predicted ultimate shrinkage values for concretes formed from these mixes are calculated to be 210, 223 and 206 $\mu\varepsilon$, respectively. These are in reasonable agreement with the ultimate shrinkage values of 173, 201 and 272 $\mu\varepsilon$, which are calculated by dividing the 365-day shrinkage values by the conversion factor of 0.92. The ratios of the predicted/calculated shrinkage values are 1.2, 1.1 and 0.8, respectively, which are within the acceptable range of ±20% given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. The results are shown in Table 5.5.

In contrast to the research on concretes formed from mixes containing CSAC/PFA binder blends, there has been little study of concretes containing combinations of CSAC/GGBS binders. Babu et al. [10] found that in the absence of OPC, GGBS binder contributes to strength development via its own hydration process, although this leads to only small gains in strength and occurs at a much slower rate than PFA hydration. These self-hydration and slower strength development properties of GGBS binder are confirmed by the findings discussed in Chapter 4 and in a paper of the author [44], but the strength development of GGBS is found to continue until the age of 365 days or longer. The previous studies of Babu et al. [10] and the findings in Chapter 4, which are reported in the previous study [44], confirm that GGBS binder in the presence of OPC enhances concrete strength via the pozzolanic properties resulting from its secondary hydration. However, its rate of strength development up to the age of 28 days was slower than that of a pure OPC concrete with the same binder content and water-to-binder ratio.

In contrast to the contribution of PFA binder hydration, the above-described contribution of the GGBS binder hydration process to strength gain also influences the shrinkage development of a concrete. In this regard, the K factor for GGBS binder (K_{GGBS}) in concrete in the absence of OPC binder (i.e., in the concretes formed from CSAC/GGBS mixes) is estimated to be 0.07, which is greater than that for PFA. Similarly, the K factor for CSAC/GGBS mixes ($K_{CSAC/GGBS}$) used in the GL2000 model is the sum of K_{CSAC} and K_{GGBS} with respect to the percentage (P) of CSAC and GGBS in the binder combination (i.e., $K_{CSAC} \times P_{CSAC} + K_{GGBS} \times P_{GGBS}$). Thus, the corresponding 28-day cylinder strengths, which are calculated from the tested cube strengths, and the values for $K_{CSAC\text{-}PFA}$ in mixes 65/0/0/35 and 35/0/0/65 are used in Eq. 5.4 to obtain predicted ultimate shrinkage values for concretes formed from these mixes of 179 and 147 $\mu\varepsilon$, respectively. These are in reasonable agreement with the measured long-term shrinkage values of 147 and 184 $\mu\varepsilon$, and the ratios of the predicted/calculated shrinkage value ratios are 1.2 and 0.8, which are both within the acceptable range of ±20% given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. These results are listed in Table 5.5.

5.5.3 OPC/PFA, CSAC/OPC/PFA and CSAC/OPC/GGBS binder blends

The concretes studied in this category were formed from mixes 100/0/0/0, 0/100/0/0, 37.5/37.5/25/0, 32.5/32.5/35/0, 27.5/27.5/45/0, 0/75/25/0, 0/65/35/0, 70/5/25/0, 65/10/25/0, 65/0/0/35, 35/0/0/65, 32.5/32.5/0/35 & 17.5/17.5/0/65; their shrinkage measurement results are given in Tables 5.3 and 5.4, and their shrinkage development trends are plotted in Figures 5.3 and 5.4. The shrinkage values at the age of 365 days of concretes formed from concrete mixes containing OPC/PFA binder combinations (mixes 0/75/25/0 and 0/65/35/0) are slightly lower than that of concrete formed from pure OPC concrete mix (0/100/0/0). The shrinkage reduction performance of PFA binder, as described in some previous studies [18, 24], was only obvious at early ages (28–56 days), whereas drying shrinkage continued to develop, at a decreasing rate, beyond 365 days. The slow hydration process of PFA, which only occurred in the presence of OPC, resulted in the slow development of compressive strength, but this continued to develop to 365 days as evidenced by the results. Thus, the development of autogenous shrinkage in these concretes is slow, as it is also affected by the hydration process, but does not stop until the hydration process is complete. It is therefore concluded that PFA binder in the presence of OPC only delays shrinkage development, rather than reducing the magnitude of shrinkage over the long-term.

The K factor for OPC/PFA concrete ($K_{OPC/PFA}$) in the GL 2000 model for estimating the ultimate shrinkage value of OPC/PFA concrete is the sum of K_{OPC} and $K_{PFA-OPC}$ with respect to the percentage of OPC and PFA in the binder (i.e., $K_{OPC} \times P_{OPC} + K_{PFA-OPC} \times P_{PFA}$). The shrinkage development of OPC/PFA concretes (formed from mixes 0/75/25/0 and 0/65/35/0) did not differ significantly to that of pure OPC concrete (formed from mix 0/100/0/0). This is in agreement with Neville [24], who noted that concrete shrinkage was not fundamentally affected by PFA. The $K_{PFA-OPC}$ factor is therefore estimated to be 1.0. By using these K values, the percentages of each binder and the corresponding cylinder strength of concretes formed from each OPC/PFA mix in Eq. 5.4, the estimated ultimate shrinkage values for concretes formed from mixes 0/75/25/0 and 0/65/35/0 are calculated to be 793 and 826 $\mu\varepsilon$, respectively. These are in reasonable agreement with the calculated ultimate shrinkage values based on measurements, which are 784 and 743 $\mu\varepsilon$, respectively, and are agreement with the ratios of the predicted/calculated shrinkage values of 1.0 and 1.1, respectively, as shown in Table 5.5.

As confirmed in Chapter 4 and a paper published by the author [44], sufficient $Ca(OH)_2$ is generated by the hydration of small amounts of OPC binder (i.e., 5% in a binder combinations) to activate the pozzolanic reactions of PFA and GGBS binders. Because of the contributions to concrete strength that result from these reactions, although occurring at a very slow rate, concretes containing OPC and PFA/GBB binders exhibited similar long-term strengths at the age of 365 days as those formed from pure OPC mix. However, as mentioned previously, the presence of CSAC in the binder combination did not enhance the strengthening effects of PFA binder, as there is no hydration effect interaction between these species.

For CSAC/OPC/PFA mixes, K_{CSAC}, K_{OPC} and $K_{PFA-OPC}$ are taken as 0.29, 1.0 and 1.0, as previously derived. By substituting these K factors, the percentages of each binder and the corresponding cylinder strengths of concretes formed from each CSAC/OPC/PFA mix into Eq. 5.4, as appropriate, the estimated ultimate shrinkage values for concretes formed from mixes 37.5/37.5/25/0, 32.5/32.5/35/0, 27.5/27.5/45/0, 70/5/25/0 and 65/10/25/0 are found to be 575, 640, 699, 451 and 476 $\mu\varepsilon$, respectively. These estimated results are in reasonable agreement with the calculated ultimate shrinkage values of 715, 695, 790, 367 and 398 $\mu\varepsilon$, which are based on measurements, and the ratios of the predicted/calculated shrinkage values are 0.8, 0.9, 0.9, 1.2 and 1.2, respectively. All of these estimated values are within the acceptable range of ±20% stated in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15]. All results are listed in Table 5.5.

As indicated by Neville [24], GGBS binder induces a greater initial shrinkage in concrete than do other binders, but does not result in a significant change in long-term shrinkage. The measured long-term shrinkage of concrete formed from CSAC/OPC/GGBS mixes (32.5/32.5/0/35 and 17.5/17.5/0/65), compared to that of concrete formed from the pure OPC mix (0/100/0/0), agrees with this previous finding of Neville [24]. However, the measured shrinkage values of these concretes before the age of 90 days were lower than that of the concrete formed from the pure OPC mix, which is not in line with the findings of Neville [24]. This is attributable to the presence of CSAC in the binder mixtures, as it exhibits early expansion due to ettringite formation. However, as mentioned, the measured shrinkage values at the age of 365 days of concretes formed from these two mixes containing CSAC/OPC/GGBS binder combinations were similar to that of the concrete formed from the pure OPC mix. The estimated K value for GGBS binder in the presence of OPC binder ($K_{GGBS-OPC}$) is therefore taken as 1.0, while those for CSAC and OPC binders (K_{CSAC} and K_{OPC}) remain as 0.29 and 1.0. By substituting these K factors, the percentages of each binder in binder mix and the corresponding cylinder strengths of concretes formed from mixes containing CSAC/OPC/GGBS binder blends into Eq. 5.4 as appropriate, the predicted ultimate shrinkage values for the concretes formed from mixes 32.5/32.5/0/35 and 17.5/17.5/0/65 are found to be 593 and 766 με, respectively. These agree well with the calculated ultimate shrinkage values of 662 and 701 με, and result in ratios of the predicted/calculated shrinkage values of 0.9 and 1.1 respectively, all of which are within the acceptable range of ±20% stated in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15].

5.5.4 Established predictive model and verification of its applicability

The GL2000 model enables the prediction of ultimate shrinkage values for concretes that contain only OPCs as binders, namely types I, II and III, as classified in ASTM C150-07 ("Standard Specification for Portland Cement"). Therefore, in this study, K factors are derived for each of CSAC, OPC, PFA and GGBS binders and their various combinations. These are used in the newly developed predictive model (Eq. 5.5) to estimate the ultimate shrinkage values of concretes containing combinations of multiple binders.

$$\varepsilon_{shu} = 900K_{BC}\left(\frac{30}{fcm_{28}}\right)^{1/2}\ \mu\varepsilon \qquad \text{(Eq. 5.5)}$$

where K_{BC} is the combined K factor of the binder combination calculated by $\Sigma(K_B \times P_B)$, in which P_B represents the % of the binder material B in the binder combination used. The K factors for individual binder materials are given below.

K_{CSAC}	= 0.29	(CSAC)
K_{OPC}	= 1.0	(OPC)
K_{PFA}	= 0.05	(PFA in absence of OPC)
$K_{PFA-OPC}$	= 1.0	(PFA in presence of the % of OPC adopted in this study)
K_{GGBS}	= 0.07	(GGBS in absence of OPC)

$K_{GGBS\text{-}OPC}$ = 1.0 (GGBS in absence of OPC)

The above K factors are used in Eq. 5.3 to predict the ultimate shrinkage values (ε_{shu}) of concretes formed from mixes containing various binder combinations, based on the GL2000 model in ACI 209.2R-08 ("Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete") [15].

In Equation 5.3, K_{BC} is calculated from the combined effect of all binders (K_{CSAC}, K_{OPC}, K_{PFA}, $K_{PFA\text{-}OPC}$, K_{GGBS} and $K_{GGBS\text{-}OPC}$) with respect to their percentages in the binder, i.e., combined K factor = $\Sigma(K_B \times \%_B)$, where B is the binder, K_B is the individual K factor for B (as listed above) and $\%_B$ is the percentage of B in the total binder content. The combined K factors for the different binder combinations used in the concrete mixes in this study are listed in Table 8. In addition, a comparison of the predicted ultimate shrinkage and the measured long-term shrinkage values is listed in Table 8 and plotted in Figure 5. For this curve, the coefficient of determination of 0.9 shows that the estimates of the predicted ultimate shrinkage values compare well to the ultimate shrinkage values calculated from the measured values at 365 days. In addition, all of the ratios between the individual predicted ultimate shrinkage values and calculated ultimate shrinkage values are in the range of 0.8 to 1.2, which is within the acceptable range of ±20% given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15].

Based on the above, the predictive model and the K factors developed in this study are considered to be sufficiently accurate to use for predicting the ultimate shrinkage value of a concrete formed from a mix containing combinations of the stated binders. Such predictions will be useful at the design stage for structural designers considering the suitability of a particular concrete, including the risk of crack formation, the loss of prestress and other potential defects related to ultimate dimensional change resulting from shrinkage development.

As this study only examined the shrinkage performance of concretes containing various combinations of CSAC, OPC, PFA and GGBS binders and in which the water-to-binder ratio was 0.45, concretes containing these binders and having other water-to-binder ratios may exhibit different magnitudes of shrinkage performance, although the influence of the binder combination should be similar. As mentioned earlier, shrinkage development is due to autogenous shrinkage and drying shrinkage, with only the former being dependent on the hydration of different binders. As such, the shrinkage development trends of concrete with higher water-to-binder ratios may be more dependent on drying shrinkage, which results from the loss of moisture from a concrete matrix to the atmosphere. If so, the equations developed for predicting the shrinkage performance of different binder combinations may only be applicable to concretes that have a water-to-binder ratio of 0.45 or less, which is deemed sufficient to describe most concretes that require early strength and which are formed from mixes containing CSAC binder alone or in combination with other binders, such as OPC, PFA and GGBS. Nevertheless, studies on the effect of variations in water-to-binder ratios on the performance of concretes formed from mixes containing various binder combinations of CSAC, OPC, PFA and GGBS are recommended.

Although the K factors of different binders for use in the GL2000 model are dependent on the interactions of different combinations of CSAC, PFA or GGBS binders blended with OPC binder, the most commonly used percentage contents of these binders are examined in this study.

The predicted ultimate shrinkage values are calculated using Equation 5.3, which is developed from the GL2000 model and the derived K factors for each binder. The ultimate shrinkage value of each concrete represents the predicted ultimate change in the size of the concrete with respect to its initial hardened dimension. Concretes that incorporate CSAC binder performed differently from OPC concretes, as the formation of ettringite crystals in CSAC at early ages induces expansion immediately after hardening, a process that stops within one to several days [47] and is subsequently gradually offset by shrinkage. When the reverse direction of dimensional change (i.e., from a net expansion to a net shrinkage) is observed, the immediate previously measured shrinkage value is taken as the starting point for net shrinkage, and its measured shrinkage value is taken as the shrinkage datum for correction (ε_{shd}). Subsequently, the corrected shrinkage values (CSVs) at the age of 365 days ($\varepsilon_{csh\text{-}365}$) are calculated by subtracting the shrinkage datum from the measured shrinkage value at the age of 365 days, as follows.

$$\varepsilon_{csh\text{-}365} = \varepsilon_{sh\text{-}365} - \varepsilon_{shd} \qquad \text{(Eq. 5.6)}$$

The CSVs at 365 days are used to calculate the corrected ultimate shrinkage value with respect to the zero point, i.e., where expansion stops and shrinkage begins. By replacing the $\varepsilon_{sh\text{-}365}$ and ε_{shu} in Eq. 5.6 by the corrected shrinkage values at 365-day ($\varepsilon_{csh\text{-}365}$) and the corrected ultimate shrinkage value (ε_{cshu}) respectively, Eq. 5.6 becomes:

$$\varepsilon_{csh\text{-}365} = 0.92\varepsilon_{cshu} \qquad \text{(Eq. 5.7)}$$

where $\varepsilon_{csh\text{-}365}$ is the corrected shrinkage value at 365 days and ε_{cshu} is the corrected ultimate shrinkage value.

For example, for the concrete mix 100/0/0/0, Eq. 5.6 becomes:

$$\varepsilon_{csh\text{-}365} = \varepsilon_{sh\text{-}365} - \varepsilon_{shd} = -190 - 256 = -446\ \mu\varepsilon$$

Substituting this value into Eq. 5.7 gives

$$\varepsilon_{cshu} = \varepsilon_{csh\text{-}365} \div 0.92 = -446 \div 0.92 = -485\ \mu\varepsilon$$

By substituting the values of f = 33, t_c = 1 and α =1 into Eq. 5.1 and using the corrected ultimate shrinkage value (ε_{cshu}) instead of the ultimate shrinkage value, the equation becomes:

$$\varepsilon_{tc} = \varepsilon_{cshu} \frac{(t-1)^1}{33+(t-1)^1} \qquad \text{(Eq. 5.8)}$$

where ε_{tc} is the corrected shrinkage value at age t.

As $\varepsilon_{tc} = \varepsilon_t - \varepsilon_{shd}$, therefore, $\varepsilon_t = \varepsilon_{tc} + \varepsilon_{shd}$

Again, taking mix 100/0/0/0 as an example, the shrinkage value at 28 days can be substituted into Eq. 5.8 to give the following calculation:

$$\varepsilon_{28} = \varepsilon_{cshu} \frac{(28-1)^1}{33+(28-1)^1} + \varepsilon_{shd}$$

$$= -485 \times \frac{(28-1)^1}{33+(28-1)^1} + 256 \quad = \quad 28\ \mu\varepsilon$$

The estimated shrinkage values at all ages for all concrete mixes are calculated similarly, and are listed in Table 5.6 for comparison with the measured shrinkage values. The calculated shrinkage values are plotted against the measured shrinkage values in Figures 5.6 to 5.25. The coefficients of determination indicate that there are good correlations between the two sets of data. This verifies that Equations A-1 and A-99 given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15] are also applicable for predicting the ultimate shrinkage values and interim shrinkage values of concretes containing various combinations of CSAC, OPC, PFA and GGBS binders, provided that the K factors used in Equation A-99 are accurately derived for each of these binders.

5.6 Conclusions and limitations

The findings show that the long-term shrinkage of concrete containing the studied binders is dependent on the 28-day compressive strength and the binder combination. Shrinkage results for concrete mixes with various binder combinations provide evidence that OPC induces most shrinkage among the binder materials in this study. For concrete mixes with OPC content in the binder combination reaches 17.5% or above, their shrinkage performance is close to that of the pure OPC concrete and is much higher than other concrete mixes with only 5 – 10% of OPC. On the other hand, both PFA and GGBS do not exhibit significant impact to the shrinkage performance when OPC is not present. Based on these data and the GL2000 model, a predictive model is established. However, as the GL2000 model only provides predictions based on K factors for the shrinkage of concretes containing OPC types I, II and III, as classified in ASTM C150-07 ('Standard Specification for Portland Cement') [19], different K factors for other binders and their combinations that are commonly used in concrete study are derived. These K factors are then used in the GL2000 model to predict the ultimate shrinkage of concretes containing these other binders. Thus, this work fills a key research gap, as summarised below.

Revised predictive model for ultimate shrinkage:

$$\varepsilon_{shu} = 900K_{BC}\left(\frac{30}{fcm_{28}}\right)^{1/2}\ \mu\varepsilon \qquad \text{(Eq. 5.5)}$$

where K_{BC} is the combined K factor of the binder combination, calculated from $\Sigma(K_B \times \%_B)$, in which B represents the binder(s) used. The K factors for individual binders are given below.

K_{CSAC} = 0.29 (CSAC)

K_{OPC} = 1.0 (OPC)

K_{PFA} = 0.05 (PFA in absence of OPC)

$K_{PFA\text{-}OPC}$ = 1.0 (PFA in presence of the % of OPC adopted in this study)

K_{GGBS} = 0.07 (GGBS in absence of OPC)

$K_{GGBS\text{-}OPC}$ = 1.0 (GGBS in presence of the % of OPC adopted in this study)

The above K factors and Eq. 5.5 are used to predict the ultimate shrinkage values (ε_{shu}) of concretes formed from mixes containing various binder combinations, based on the GL2000 model in ACI 209.2R-08: ("Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete") [15].

The predicted ultimate shrinkage values (ε_{shu}) are calculated as $\varepsilon_{shu} = 900K\left(\frac{30}{fcm_{28}}\right)^{1/2}$ in units of $\mu\varepsilon$, where the K factor is calculated from the combined effect of all binders (K_{CSAC}, K_{OPC}, K_{PFA}, $K_{PFA\text{-}OPC}$, K_{GGBS} and $K_{GGBS\text{-}}$

$_{OPC}$) with respect to their percentages in the concrete mix. That is, a combined K factor = $\Sigma(K_B \times P_B)$, where B is the binder of interest that is present in the binder combination, K_B is the individual K factor for B, as listed above, and P_B is the percentage content of B in the binder combination.

The combined K factors for different binder combinations used in the concrete mixes in this study are calculated and listed in Table 5.5. A comparison of the predicted ultimate shrinkage values of the concretes formed from these mixes with the measured long-term shrinkage values of these concretes is given in Table 5.5 and plotted in Figure 5.5. For this curve, the correlation of determination of 0.9 shows that the predicted ultimate shrinkage values compare well to the ultimate shrinkage values calculated from the measured values at 365 days. In addition, all of the ratios between the individual predicted ultimate shrinkage values and the calculated ultimate shrinkage values are in the range of 0.8 to 1.2, which is within the acceptable range of ±20% given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15].

Eq. 5.8 is derived from Equation A-1 given in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15] to validate the predicted ultimate shrinkage values and measured shrinkage values at interim ages from 2 to 365 days. In concretes that incorporate CSAC binder, expansion is exhibited at the initial stage and is later gradually offset by shrinkage. The measurements at various concrete ages identify the point of maximum expansion that can be taken as the zero point for the commencement of shrinkage. The measured 365-day shrinkage value is then used to calculate the corrected 365-day shrinkage value by subtracting the reading at the zero point. This result is substituted into Eq. 5.7 to calculate the predicted corrected ultimate shrinkage value. The calculated shrinkage values at different ages are then obtained from Eq. 5.6, which is derived from Equation A-1 in ACI 209.2R-08 ("Guide for modelling and calculating shrinkage and creep in hardened concrete") [15], for comparison with the measured shrinkage values at corresponding ages. Good correlations between the calculated and measured shrinkage values are obtained, as shown in Figures 5.6 to 5.25. Equations A-1 and A-99, given in the above-cited ACI report for concretes using OPC types I, II and III, are both verified as applicable to concretes containing the other binder combinations examined in this study (CSAC, OPC, PFA and GGBS), provided that the newly derived K factors for these binders are used.

The above findings show that the predictive model and the K factors developed in this study are sufficiently accurate for predicting the ultimate shrinkage values of concretes containing combinations of CSAC, OPC, PFA and GGBS binders. Such predictions will be useful at the design stage for structural designers considering the risk of crack formation, loss of prestress and other potential defects in concrete that are related to its ultimate dimensional change, which results from shrinkage development.

Only the shrinkage performance of concretes containing various combinations of CSAC, OPC, PFA and GGBS binders, and with a total binder content of 420 kg/m^3 and a water-to-binder ratio of 0.45, were examined in this study. Concretes with other total binder contents and water-to-binder ratios may give different magnitudes of shrinkage performance. As mentioned earlier, shrinkage development results from autogenous shrinkage and drying shrinkage, where the former is dependent on the consumption of moisture in a concrete during the hydration of whichever binder combinations it contains, and the latter is dependent on the loss of moisture from a concrete to the atmosphere. Accordingly, the shrinkage development trends of concretes with the same total binder content and combination but higher water-to-binder ratios may be more dependent on drying shrinkage than those studied here. As a result, the equations developed for predicting the shrinkage performance of concretes containing various binder combinations may only be applicable to concretes with a water-to-binder ratio of 0.45 or less. This water-to-binder ratio range is sufficient to describe most concretes that require early strength and are thus formed from mixes containing CSAC or its combination with other binders, such as OPC, PFA and GGBS. Nevertheless, it is recommended that the effect of variations in the total binder content and water-to-binder ratios, and of different combinations of CSAC, OPC, PFA and GGBS binders, on shrinkage development trends in concretes are studied.

Although the K factors for different binders, as used in the GL2000 model, are dependent on the interactions of various combinations of CSAC, PFA or GGBS binders blended with OPC binder, the most commonly used percentage contents of these binders are examined in this study.

The study results in this chapter have been published in a paper entitled ‘Model for predicting shrinkage of concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS’ in the *Journal of Building Engineering* 32 (2020), p. 101671 [47].

Table 5.1 Shrinkage of concretes of different ages formed from mixes containing CSAC/OPC binders

Mix	2 days	7 days	28 days	56 days	90 days	180 days	365 days
	με (+ = expansion; - = shrinkage)						
100/0/0/0	256	135	28	-18	-35	-148	-190
75/25/0/0	121	-54	-227	-269	-297	-339	-394
50/50/0/0	-58	-160	-419	-592	-629	-602	-669
25/75/0/0	-62	-155	-462	-594	-648	-697	-711
5/95/0/0	-88	-190	-397	-608	-591	-586	-653
0/100/0/0	-76	-188	-436	-597	-612	-660	-687

Table 5.2 Shrinkage of concretes of different ages formed from mixes containing CSAC/PFA binders

Mix	2 days	7 days	28 days	56 days	90 days	180 days	365 days
	με (+ = expansion; - = shrinkage)						
100/0/0/0	256	135	28	-18	-35	-148	-190
75/0/25/0	105	154	132	-26	-31	-125	-159
65/0/35/0	147	167	135	-21	-78	-159	-185
55/0/45/0	189	71	-42	-153	-174	-199	-250
0/100/0/0	-76	-188	-436	-597	-612	-660	-687
65/0/0/35	178	88	-47	-64	-70	-86	-135
35/0/0/65	139	-26	-53	-67	-80	-106	-169

Table 5.3 Shrinkage of concretes of different ages formed from mixes containing CSAC/OPC/PFA binders

Mix	2 days	7 days	28 days	56 days	90 days	180 days	365 days
	με (+ = expansion; - = shrinkage)						
100/0/0/0	256	135	28	-18	-35	-148	-190
0/100/0/0	-76	-188	-436	-597	-612	-660	-687
37.5/37.5/25/0	105	-184	-411	-563	-590	-617	-658
32.5/32.5/35/0	147	-176	-473	-554	-614	-678	-639
27.5/27.5/45/0	189	-165	-362	-419	-588	-609	-727
0/75/25/0	105	-70	-183	-516	-676	-711	-721
0/65/35/0	147	-82	-179	-499	-608	-643	-684
70/5/25/0	112	-75	-68	-144	-229	-254	-338
65/10/25/0	104	-29	-23	-104	-208	-269	-366

Table 5.4 Shrinkage of concretes at different ages formed from mixes containing CSAC/OPC/GGBS binders

Mix	2 day	7 days	28 days	56 days	90 days	180 days	365 days
	με (+ = expansion; - = shrinkage)						
100/0/0/0	256	135	28	-18	-35	-148	-190
0/100/0/0	-76	-188	-436	-597	-612	-660	-687
65/0/0/35	178	88	-47	-64	-70	-86	-135
35/0/0/65	139	-26	-53	-67	-80	-106	-169
32.5/32.5/0/35	164	23	-146	-303	-692	-707	-609
17.5/17.5/0/65	96	-9	-197	-335	-687	-697	-645

Table 5.5: Comparison of predicted ultimate shrinkage (GL2000 model) with measured long-term shrinkage

Mix	28-day cube strength (MPa)	28-day cylinder strength (MPa)	P_{CSAC}	K_{CSAC}	P_{OPC}	K_{OPC}	P_{PFA}	K_{PFA} or $K_{PFA\text{-}OPC}$	P_{GGBS}	K_{GGBS} or $K_{GGBS\text{-}OPC}$	Ultimate shrinkage (με)				
											Combined K	Predicted by GL2000 model	Measured 365-day shrinkage	Calculated ultimate shrinkage	Ratio of predicted/ calculated ultimate shrinkage
100/0/0/0	55.6	44.5	100	0.29	0	1.0	0	--	0	--	0.30	214	190	207	1.0
75/25/0/0	54.5	43.6	75	0.29	25	1.0	0	--	0	--	0.48	351	394	428	0.8
50/50/0/0	57.0	45.6	50	0.29	50	1.0	0	--	0	--	0.65	474	569	618	0.8
25/75/0/0	58.6	46.9	25	0.29	75	1.0	0	--	0	--	0.83	590	711	773	0.8
75/0/25/0	36.5	29.2	75	0.29	0	1.0	25	0.2	0	--	0.24	210	159	173	1.2
65/0/35/0	27.0	21.6	65	0.29	0	1.0	35	0.2	0	--	0.21	223	185	201	1.1
55/0/45/0	23.3	18.6	55	0.29	0	1.0	45	0.2	0	--	0.19	206	250	272	0.8
0/100/0/0	58.7	47.0	0	--	100	1.0	0	--	0	--	1.00	719	687	747	1.0
37.5/37.5/25/0	48.9	39.0	37.5	0.29	37.5	1.0	25	1.0	0	--	0.74	575	658	715	0.8
32.5/32.5/35/0	44.0	35.0	32.5	0.29	32.5	1.0	35	1.0	0	--	0.77	640	639	695	0.9
27.5/27.5/45/0	39.8	31.8	27.5	0.29	27.5	1.0	45	1.0	0	--	0.81	699	727	790	0.9
0/75/25/0	48.3	38.6	0	--	75	1.0	25	1.0	0	--	1.00	793	721	784	1.0
0/65/35/0	44.5	35.6	0	--	65	1.0	35	1.0	0	--	1.00	826	684	743	1.1
5/95/0/0	55.9	44.7	5	0.29	95	1.0	0	--	0	--	0.97	708	653	710	1.0
70/5/25/0	37.4	29.9	70	0.29	5	1.0	25	1.0	0	--	0.51	451	338	367	1.2
65/10/25/0	39.1	31.3	65	0.29	10	1.0	25	1.0	0	--	0.55	476	366	398	1.2
65/0/0/35	41.8	33.4	65	0.29	0	1	0	--	35	0.3	0.22	179	135	147	1.2
35/0/0/65	31.7	25.4	35	0.29	0	1	0	--	65	0.3	0.15	147	169	184	0.8
32.5/32.5/0/35	51.3	41.0	32.5	0.29	32.5	1	0	--	35	1.0	0.77	593	609	662	0.9
17.5/17.5/0/65	40.1	32.1	17.5	0.29	17.5	1	0	--	65	1.0	0.88	766	645	701	1.1

Table 5.6 Summary of corrected 365-day and ultimate shrinkage values

Mix	Shrinkage at different ages	2 days	7 days	28 days	56 days	90 days	180 days	365 days	Ultimate shrinkage value	
									Corrected 365 days	Corrected USV (C-USV)
100/0/0/0	MSV	256*	135	28	-18	-35	-148	-190	-446	-485
	SV/C-USV	242	181	38	-47	-98	-153	-188	--	--
75/25/0/0	MSV	121*	-54	-227	-269	-297	-339	-394	-515	-560
	SV/C-USV	105	35	-131	-229	-287	-352	-392	--	--
50/50/0/0	MSV	-58	-160	-419	-592	-629	-602	-669	-669	-727
	SV/C-USV	-21	-112	-327	-454	-530	-614	-667	--	--
25/75/0/0	MSV	-62	-155	-462	-594	-648	-697	-711	-711	-773
	SV/C-USV	-23	-119	-348	-483	-564	-653	-709	--	--
75/0/25/0	MSV	105	154*	32	-26	-31	-125	-159	-313	-340
	SV/C-USV	144	102	1	-59	-94	-133	-158	--	--
65/0/35/0	MSV	147	167*	135	-21	-78	-159	-185	-352	-383
	SV/C-USV	156	108	-5	-72	-112	-156	-184	--	--
55/0/0/45/0	MSV	189*	71	-42	-153	-174	-199	-250	-439	-477
	SV/C-USV	175	116	-26	-109	-159	-214	-249	--	--
0/100/0/0	MSV	-76	-188	-436	-597	-612	-660	-687	-687	-746
	SV/C-USV	-22	-115	-336	-467	-545	-631	-685	--	--
37.5/37.5/25/0	MSV	105*	-184	-411	-563	-590	-617	-658	-763	-829
	SV/C-USV	81	-23	-268	-413	-500	-595	-655	--	--
32.5/32.5/35/0	MSV	147*	-176	-473	-554	-614	-678	-639	-786	-854
	SV/C-USV	81	-23	-268	-413	-500	-595	-655	--	--
27.5/27.5/45/0	MSV	189*	-165	-362	-419	-588	-609	-727	-916	-995
	SV/C-USV	160	36	-259	-433	-537	-652	-724	--	--
0/75/25/0	MSV	105*	-70	-183	-516	-676	-711	-721	-826	-898
	SV/C-USV	79	-33	-299	-456	-550	-653	-718	--	--
0/65/35/0	MSV	147*	-82	-179	-499	-608	-643	-684	-831	-903
	SV/C-USV	120	8	-259	-418	-512	-616	-681	--	--
5/95/0/0	MSV	-88	-190	-397	-608	-591	-586	-653	-653	-710
	SV/C-USV	-21	-109	-319	-444	-518	-599	-651	--	--
70/5/25/0	MSV	112*	-75	-68	-144	-229	-254	-338	-450	-489
	SV/C-USV	98	37	-108	-194	-245	-301	-336	--	--
65/10/25/0	MSV	104*	-29	-23	-104	-208	-269	-366	-470	-511
	SV/C-USV	89	25	-126	-215	-269	-327	-364	--	--
65/0/0/35	MSV	178*	88	-47	-64	-70	-86	-135	-313	-340
	SV/C-USV	168	126	25	-35	-70	-109	-134	--	--
35/0/0/65	MSV	139*	26	-53	-67	-80	-106	-169	-308	-335
	SV/C-USV	129	87	-12	-70	-105	-144	-168	--	--
32.5/32.5/0/35	MSV	164*	23	-146	-303	-692	-707	-609	-773	-840
	SV/C-USV	139	35	-214	-361	-449	-545	-606	--	--
17.5/17.5/0/65	MSV	96*	-9	-197	-335	-687	-697	-645	-741	-805
	SV/C-USV	72	-28	-266	-407	-492	-584	-642	--	--

Note: *The measured positive shrinkage values (expansion) marked with * are taken as the zero point, where shrinkage starts. MSV: Measured shrinkage value; C-USV: corrected ultimate shrinkage value; SV/C-USV: Shrinkage values calculated from C-USV using Equation A-1 from ACI-209.2R-08.*

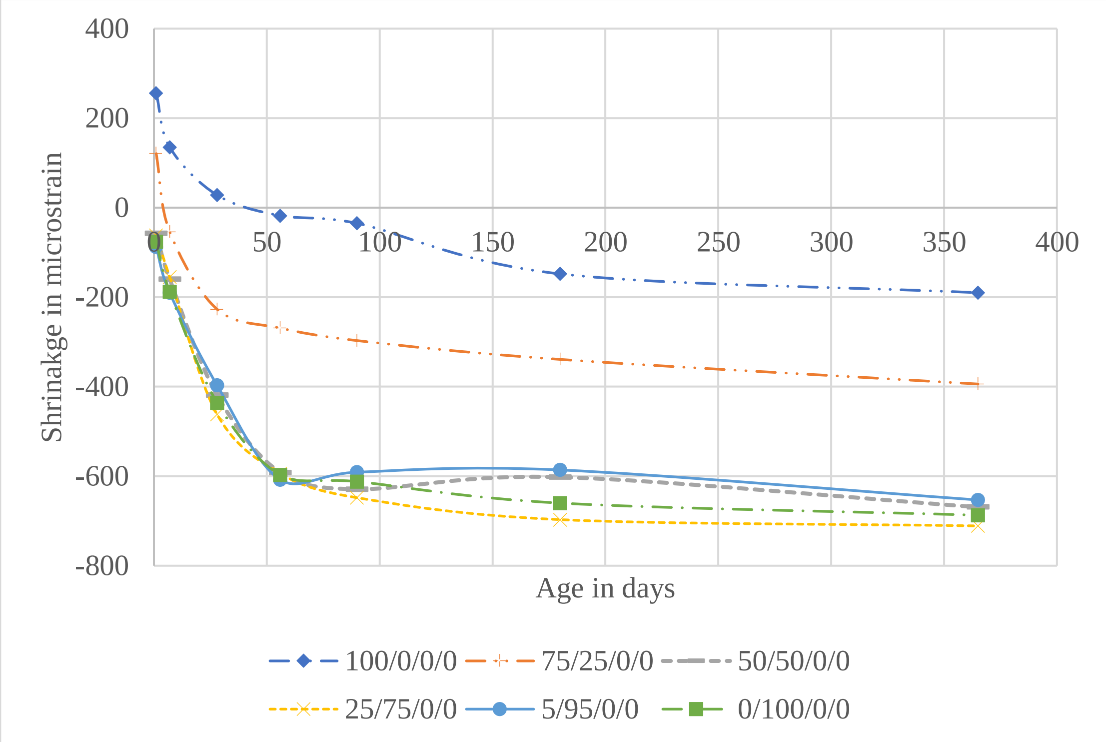

Figure 5.1 Shrinkage development trends of concretes formed from mixes containing CSAC, OPC and CSAC/OPC binders

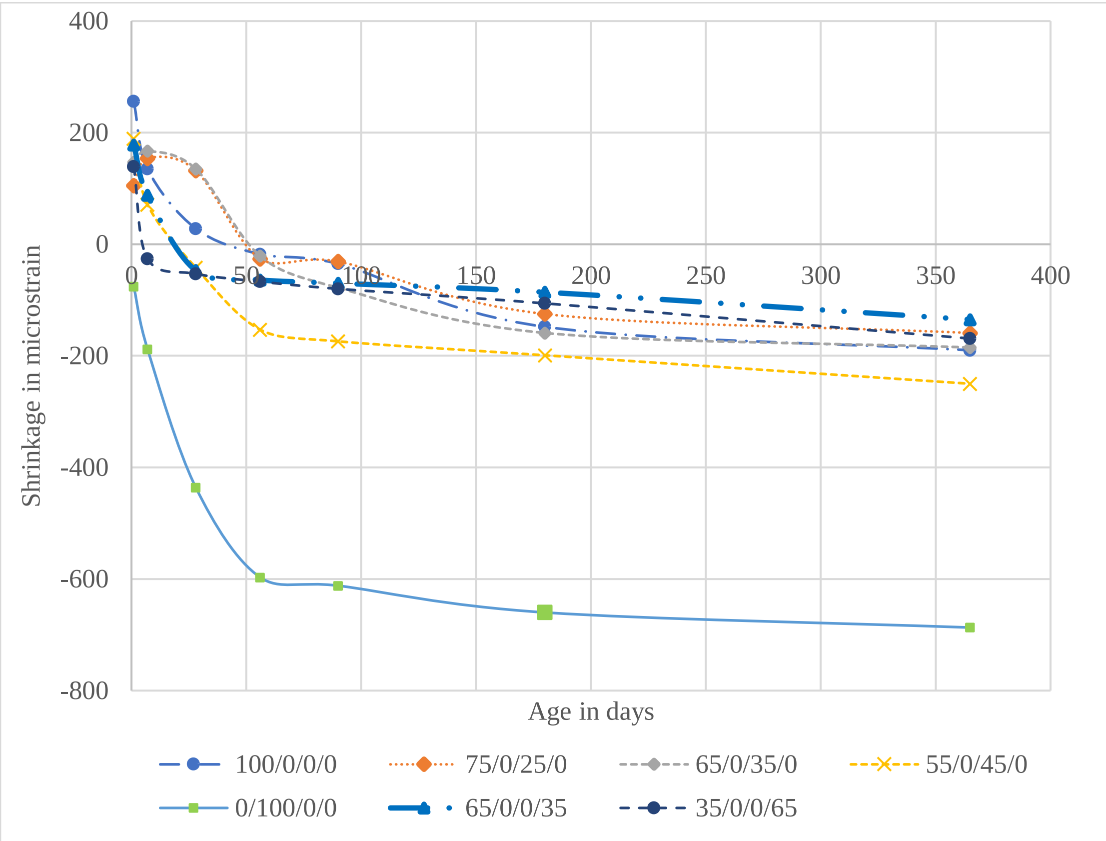

Figure 5.2 Shrinkage development trends of concretes formed from mixes containing CSAC, OPC, CSAC/PFA or CSAC/GGBS binders

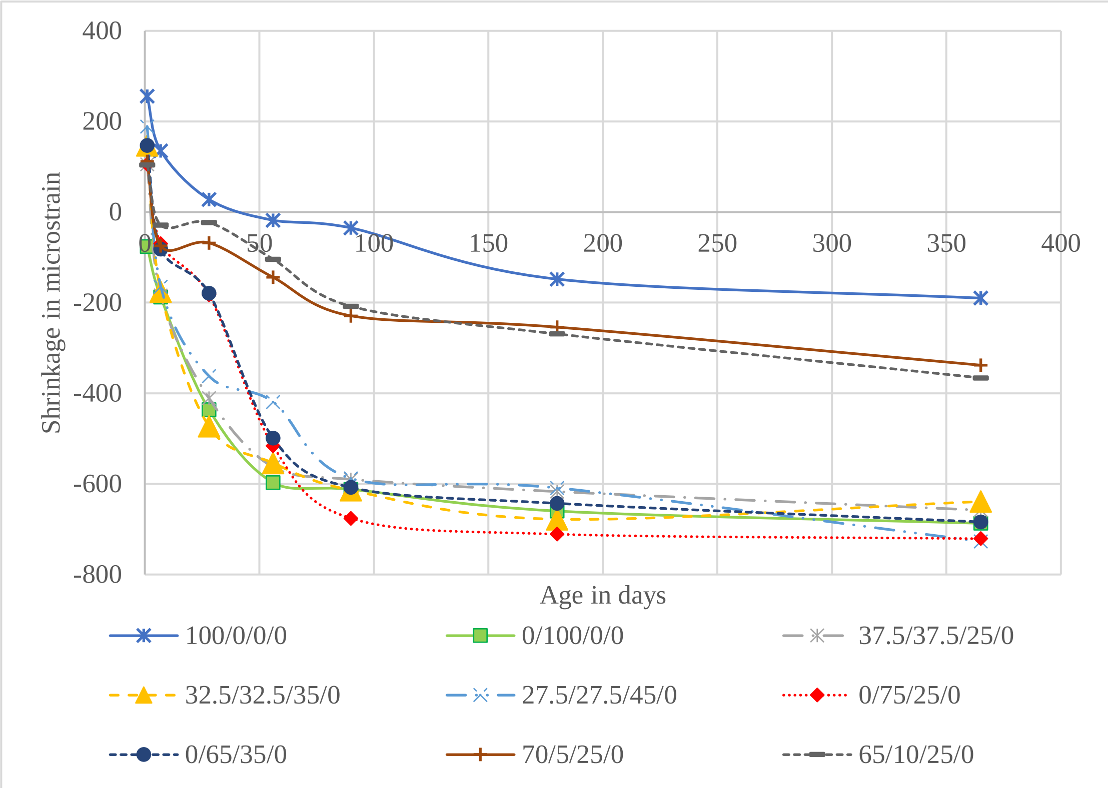

Figure 5.3 Shrinkage development trends of concretes formed from mixes containing CSAC, OPC or CSAC/OPC/PFA binders

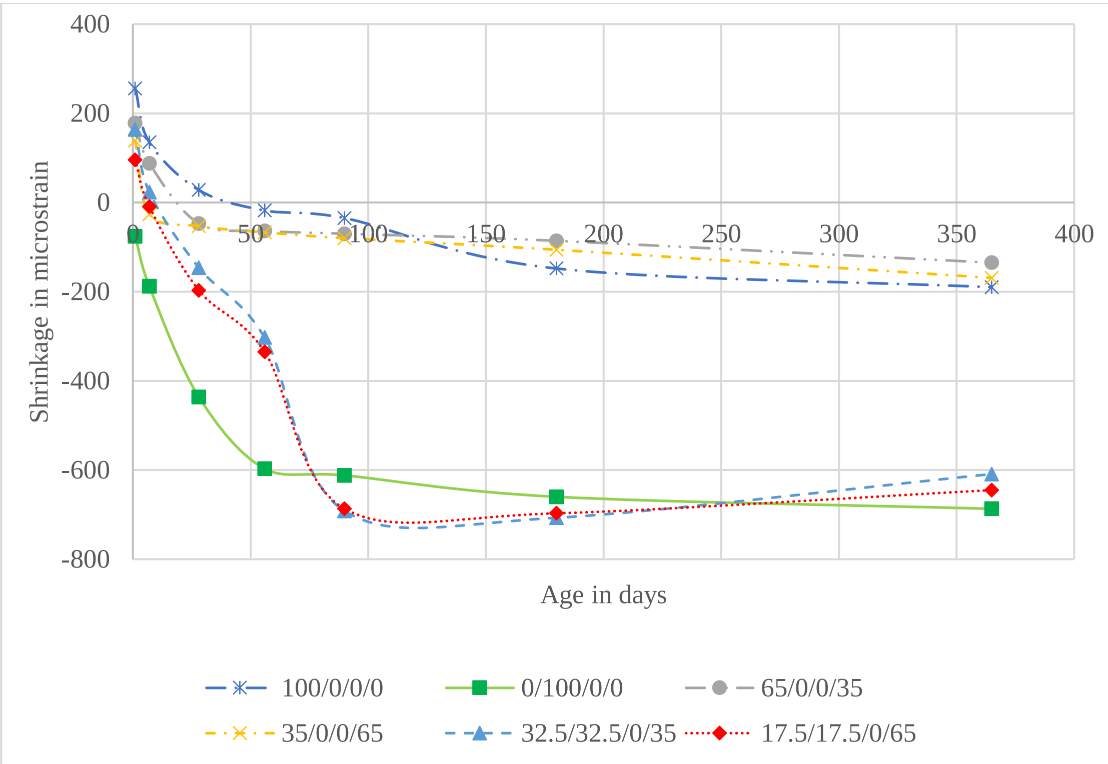

Figure 5.4 Shrinkage development trends of concretes formed from mixes containing CSAC, OPC or CSAC/OPC/GGBS binders

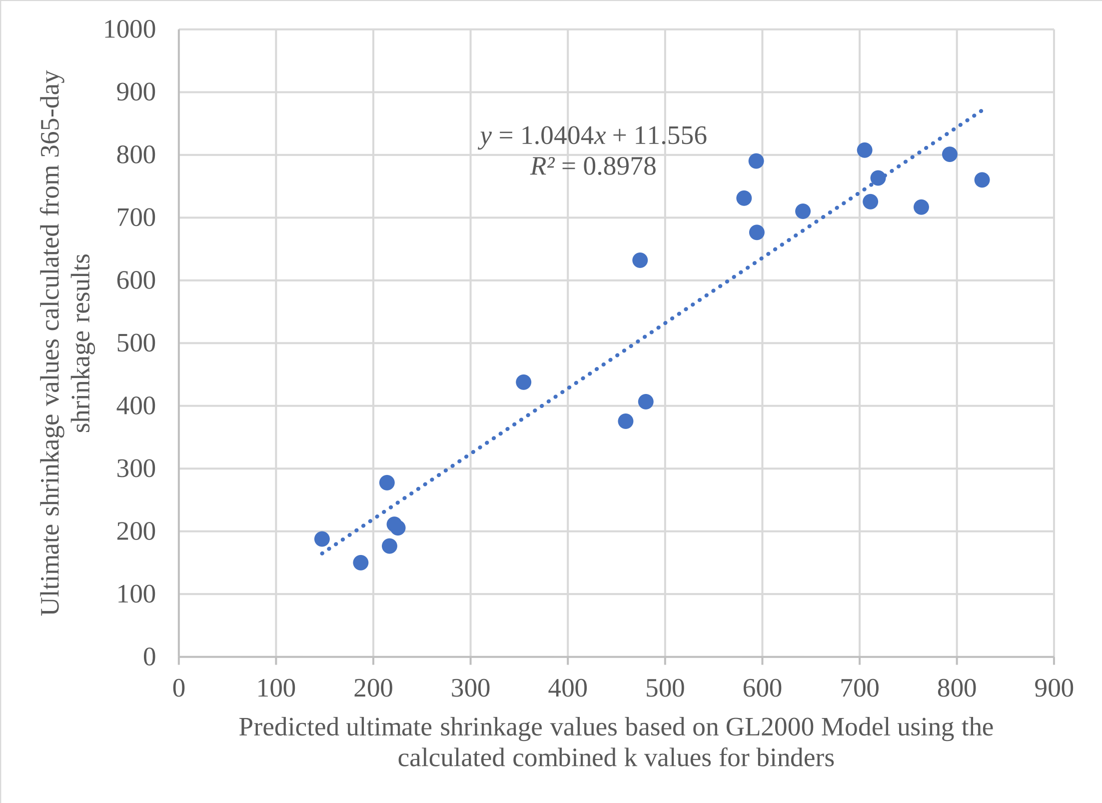

Figure 5.5 Correlation between the predicted ultimate shrinkage values based on GL2000 model and those calculated from 365-day shrinkage results

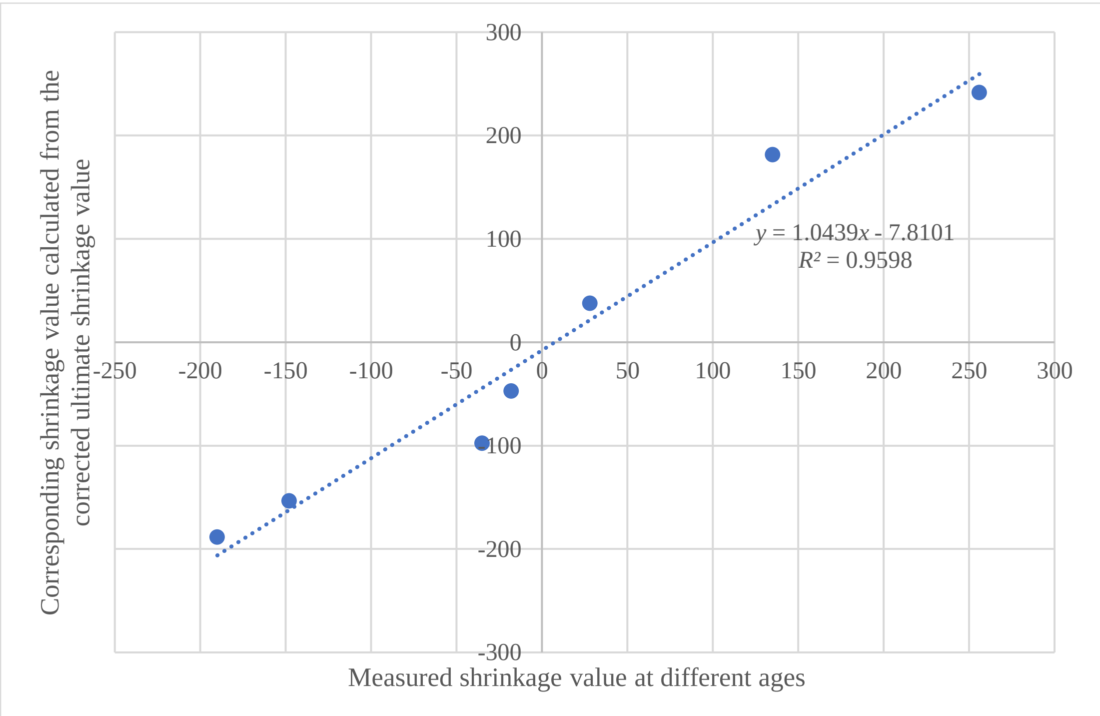

Figure 5.6 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 100/0/0/0

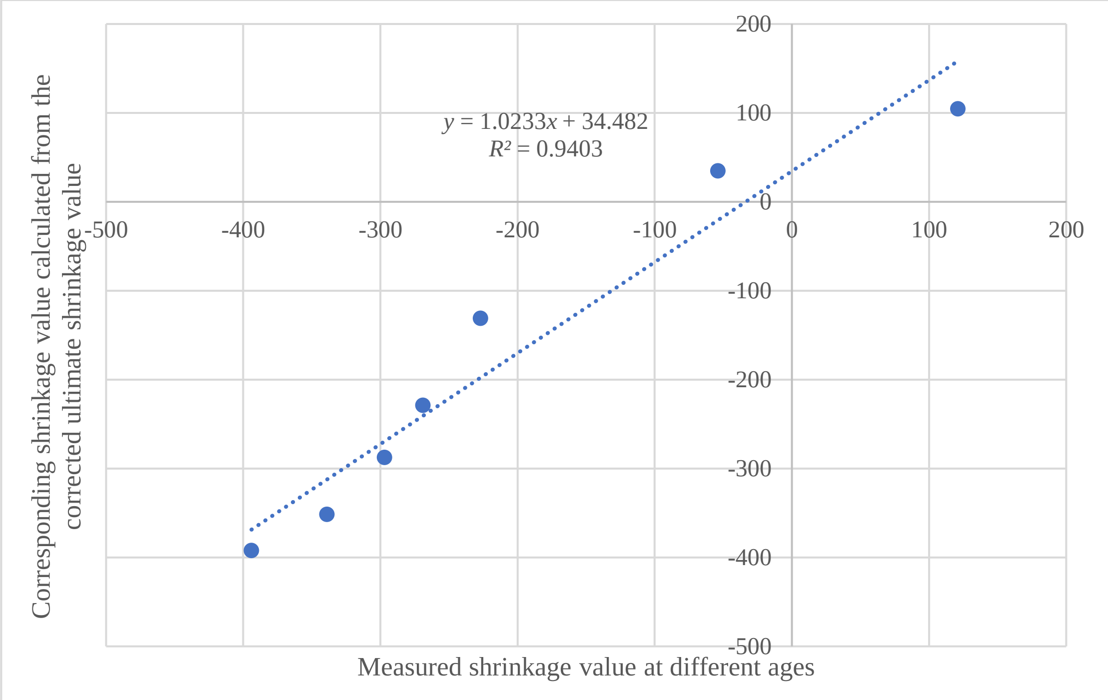

Figure 5.7 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 75/25/0/0

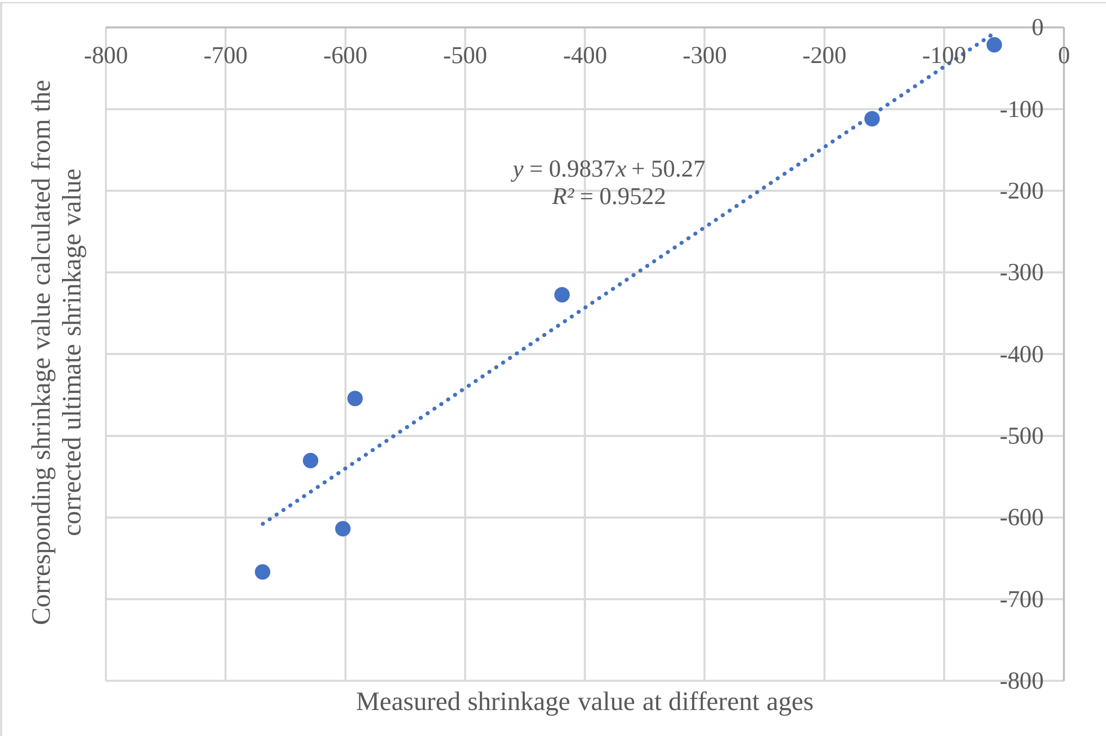

Figure 5.8 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 50/50/0/0

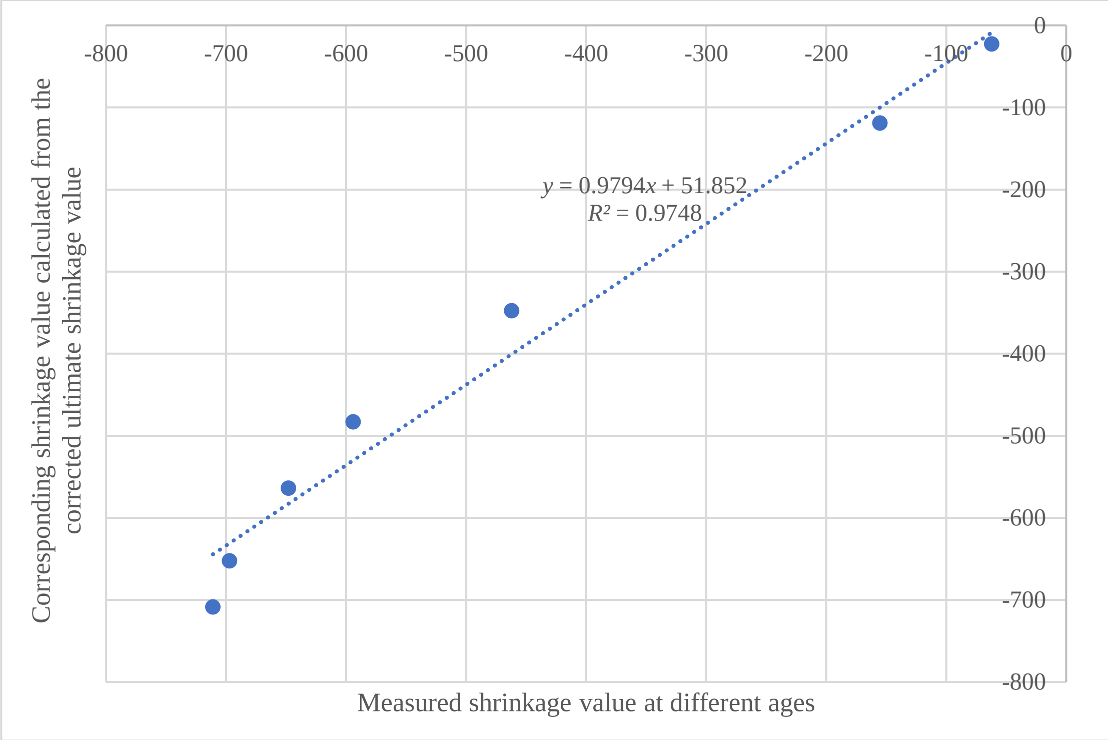

Figure 5.9 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 25/75/0/0

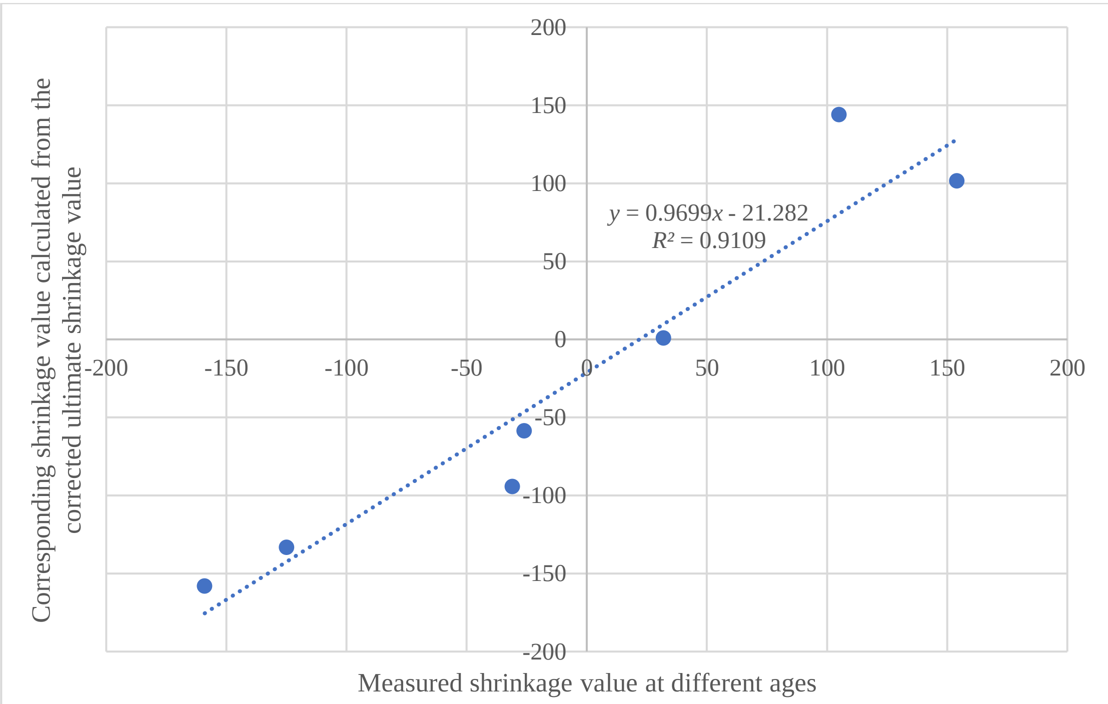

Figure 5.10 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 75/0/25/0

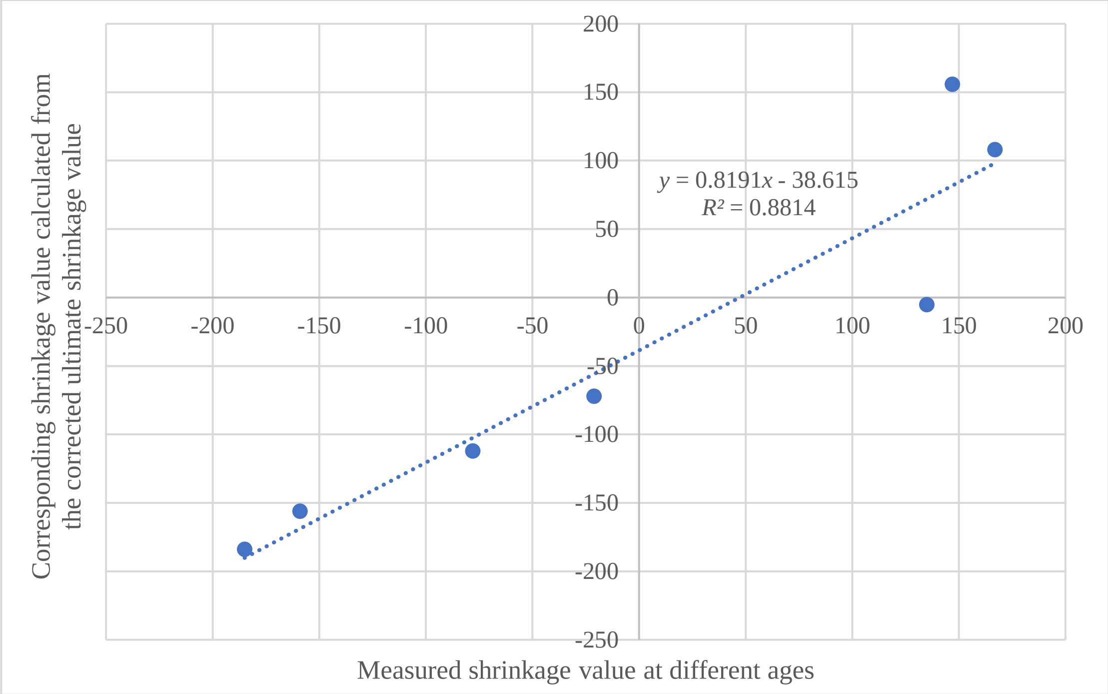

Figure 5.11 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 65/0/35/0

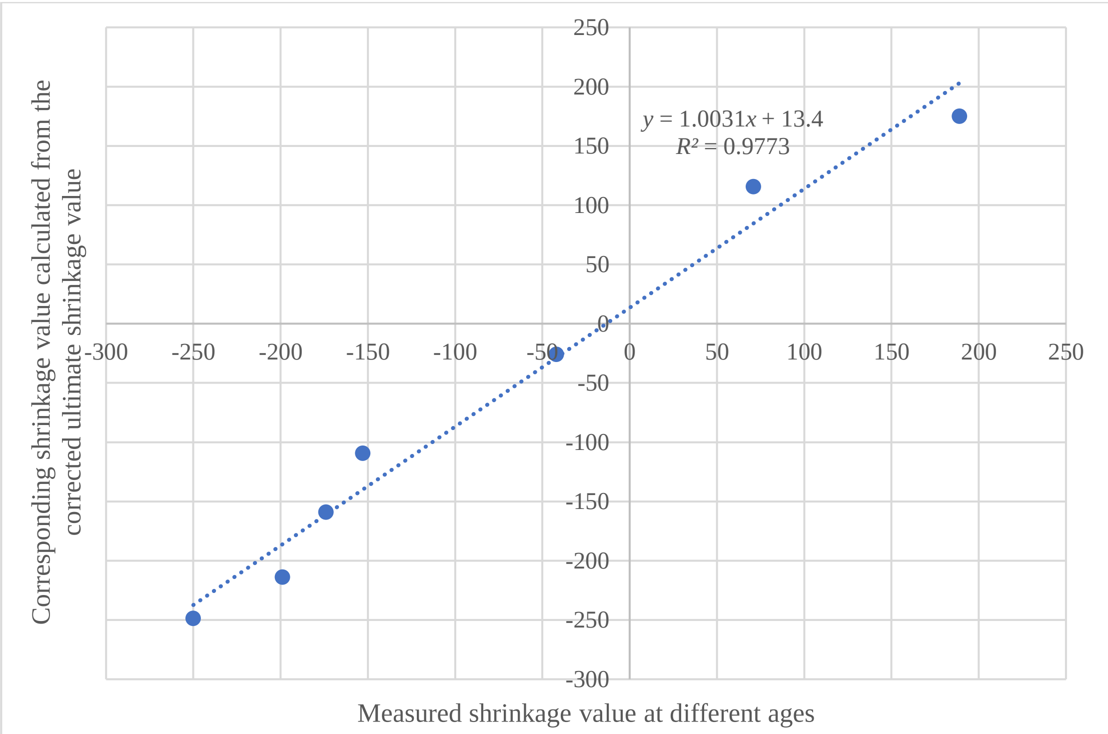

Figure 5.12 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 55/0/45/0

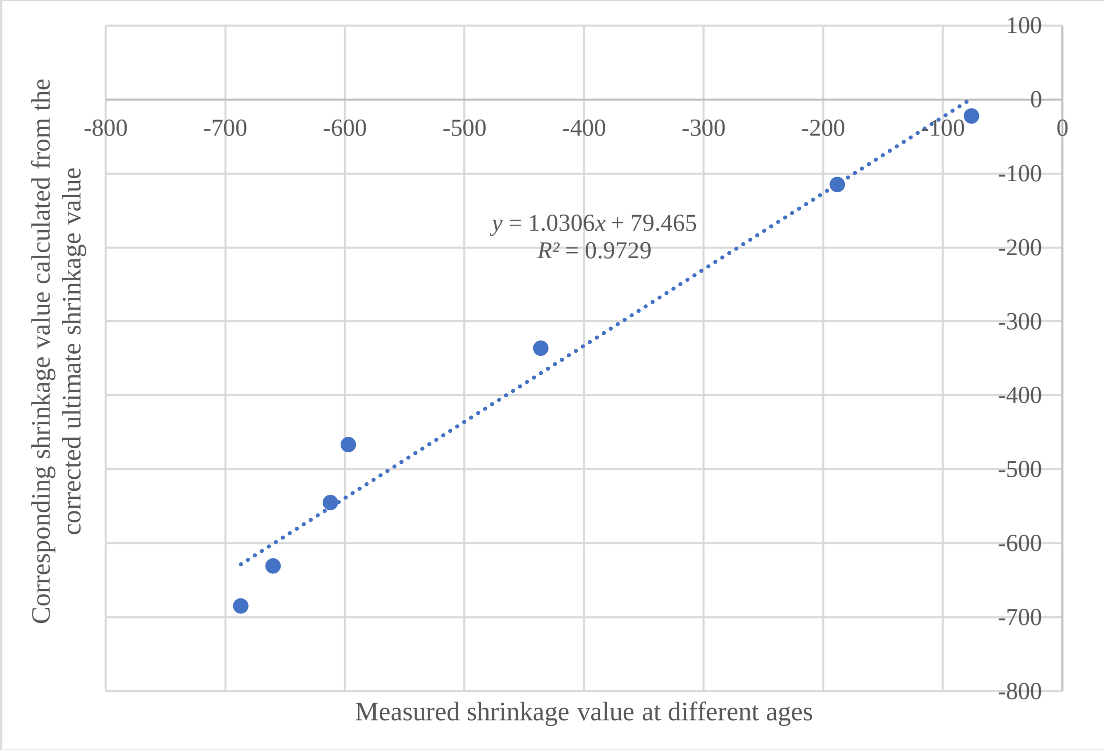

Figure 5.13 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 0/100/0/0

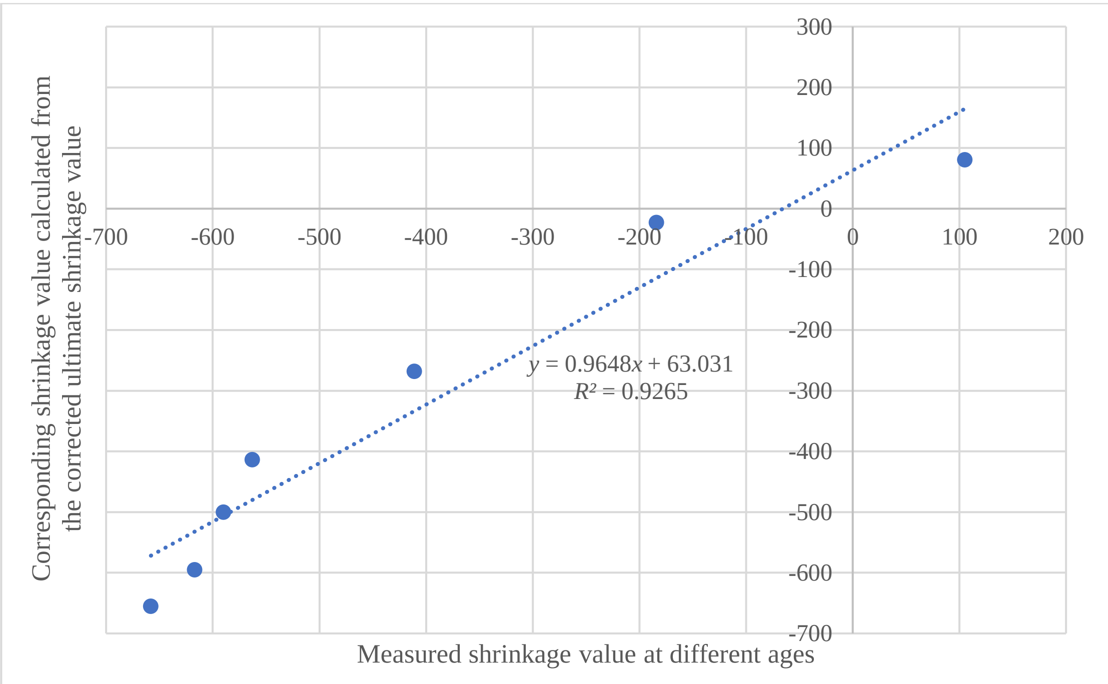

Figure 5.14 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 37.5/37.5/25/0

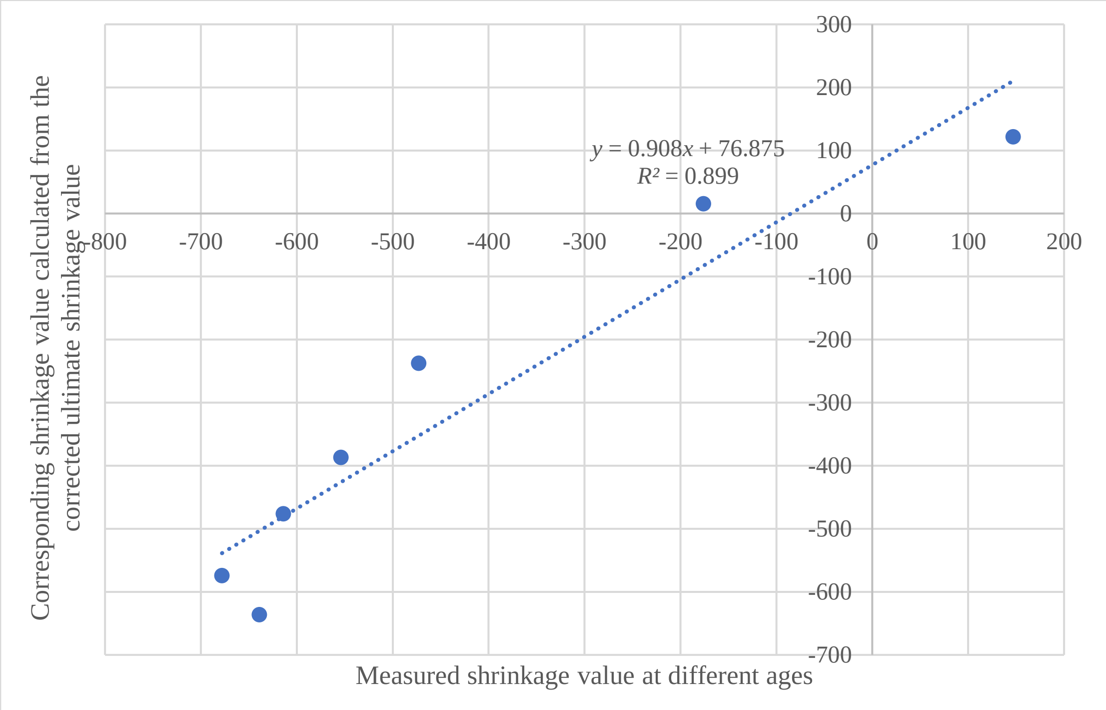

Figure 5.15 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 32.5/32.5/35/0

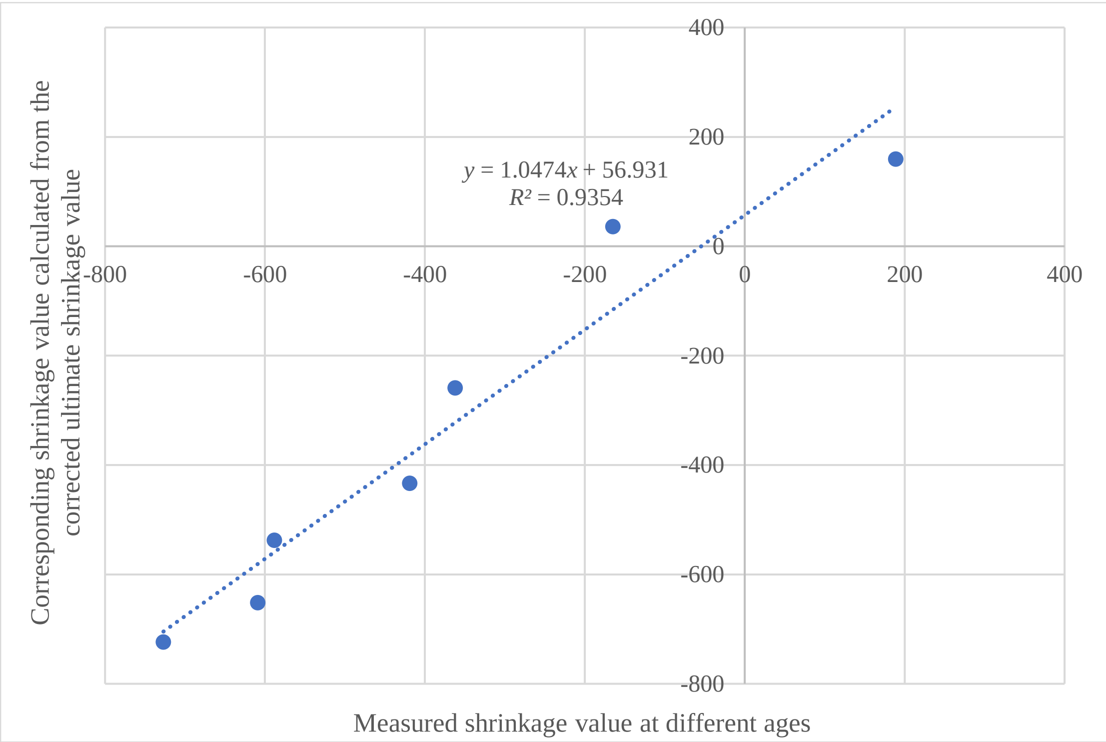

Figure 5.16 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 27.5/27.5/45/0

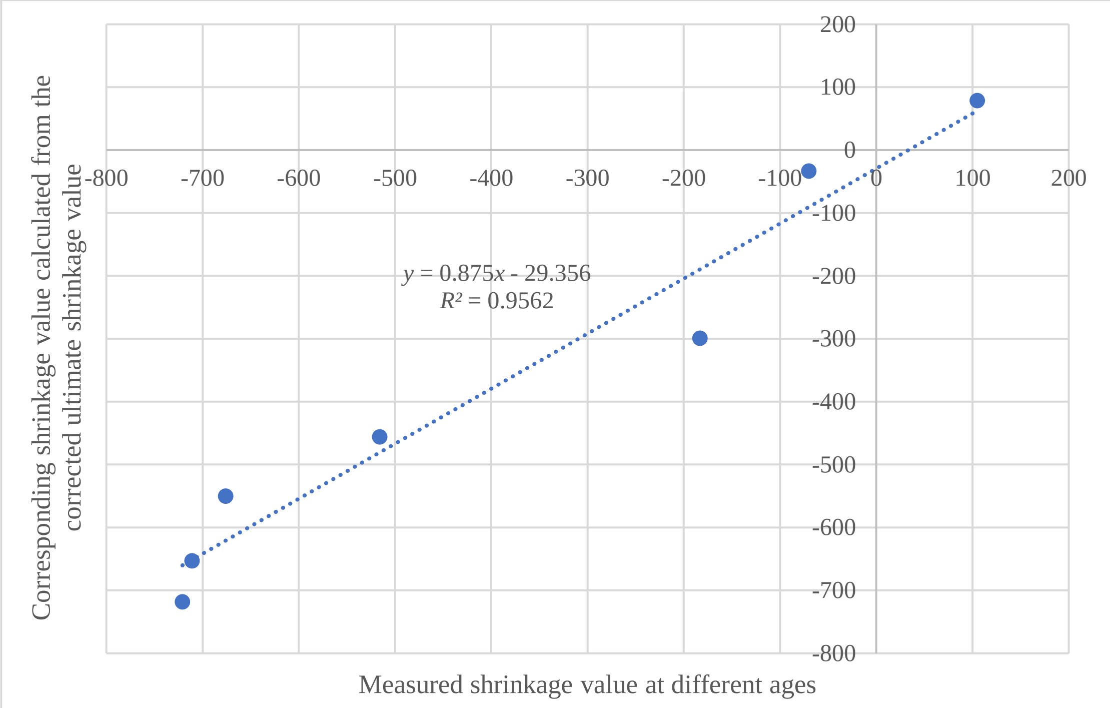

Figure 5.17 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 0/75/25/0

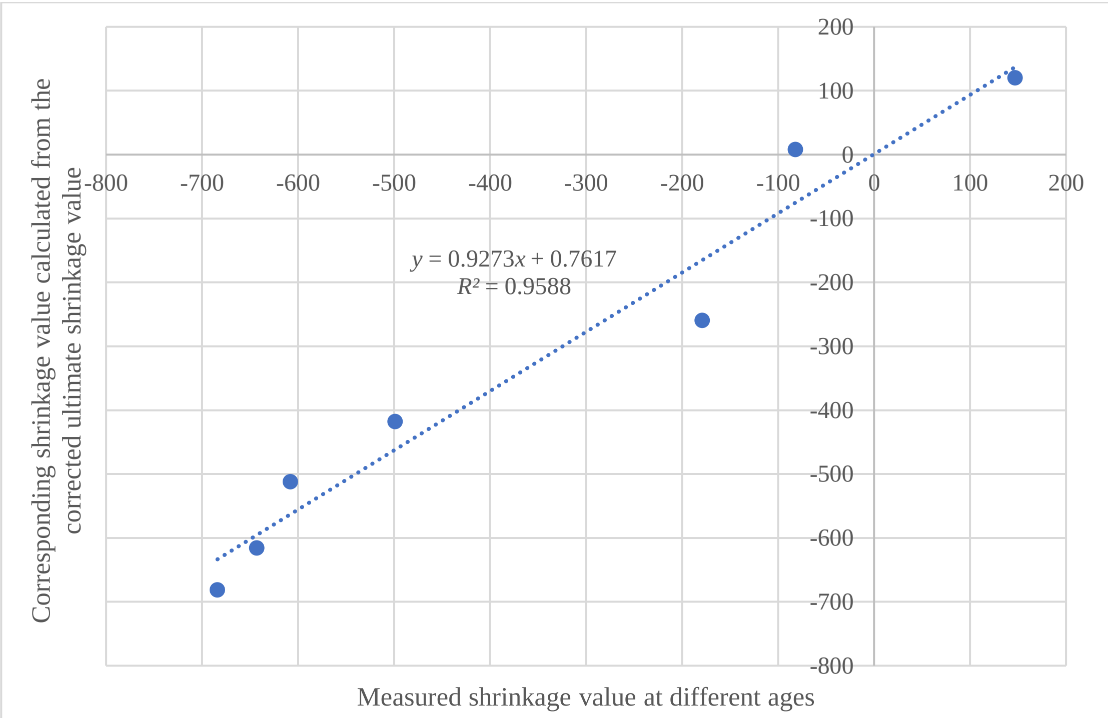

Figure 5.18 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 0/65/35/0

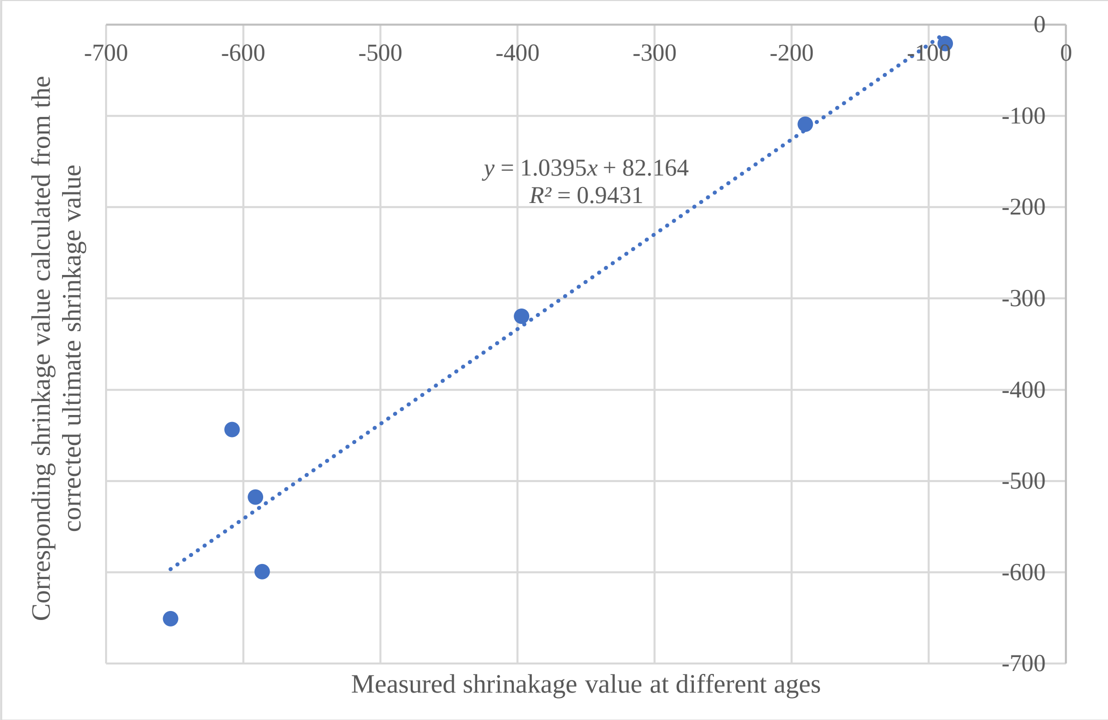

Figure 5.19 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 5/95/0/0

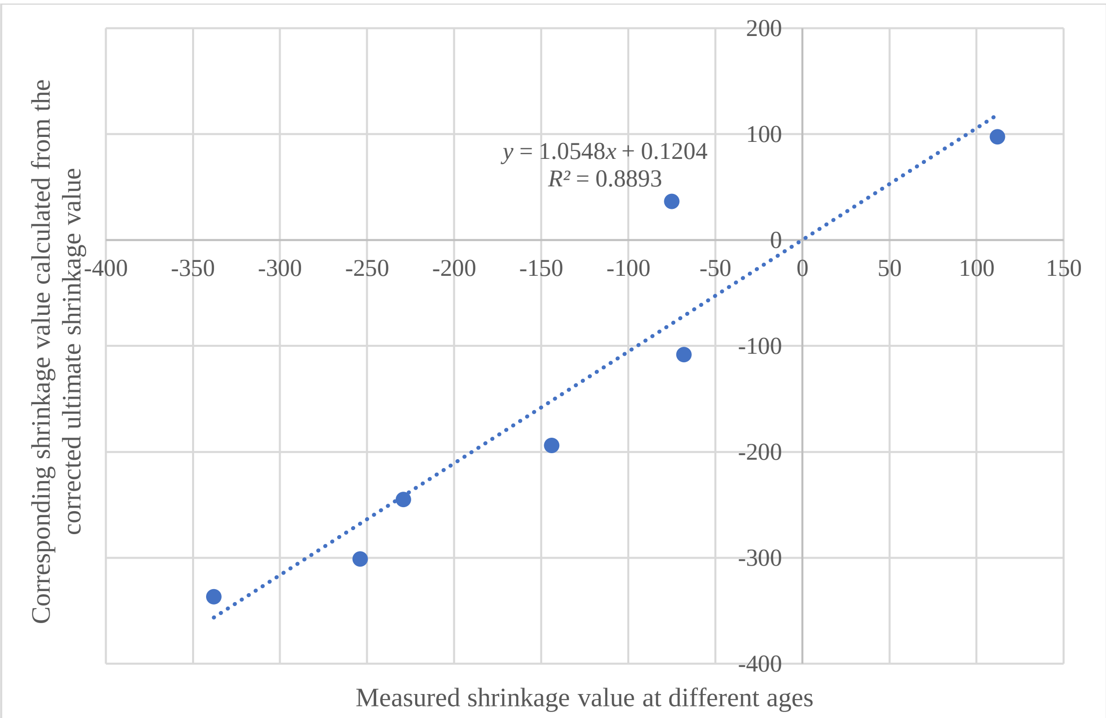

Figure 5.20 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 70/5/25/0

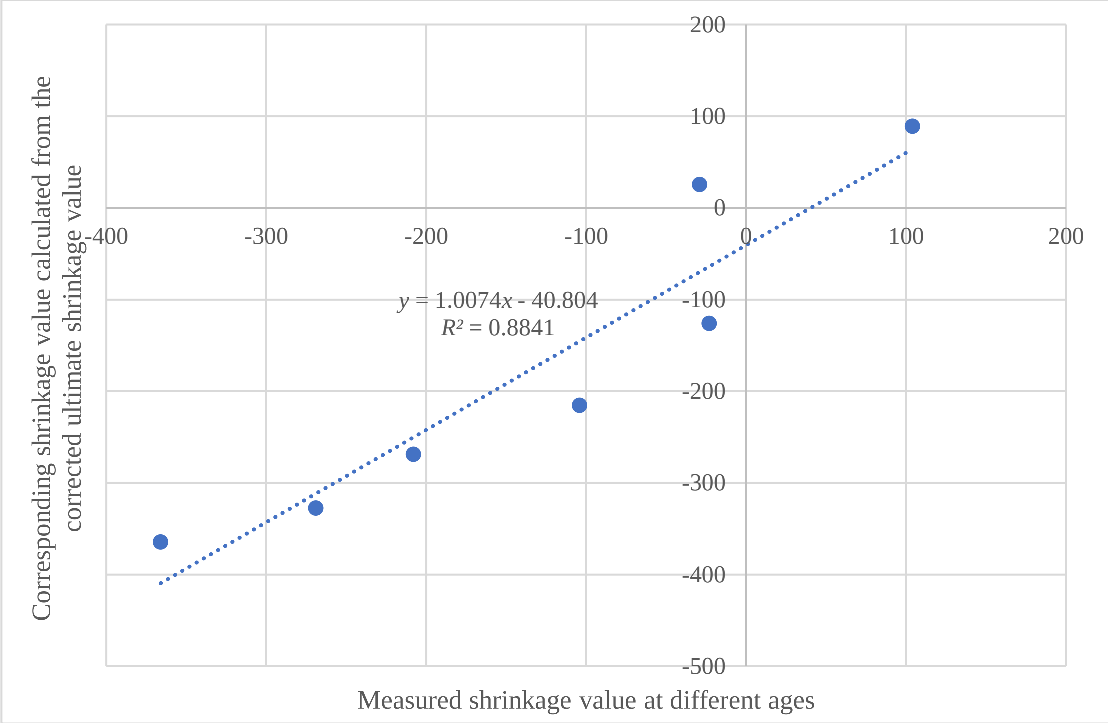

Figure 5.21 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 65/10/25/0

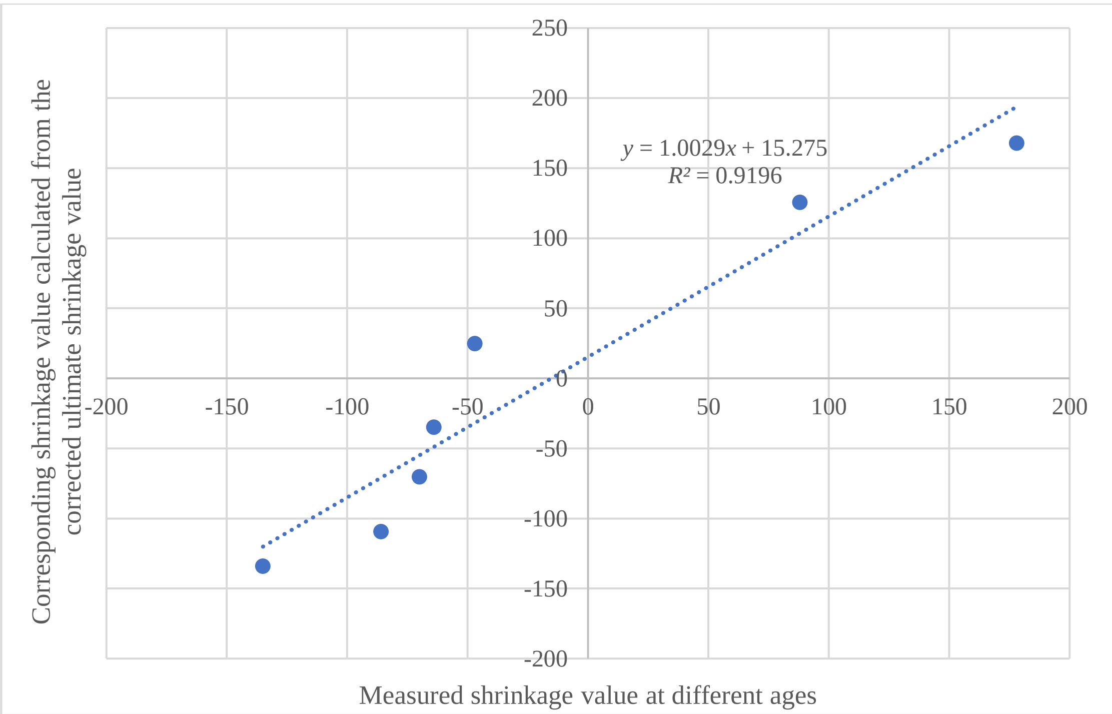

Figure 5.22 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 65/0/0/35

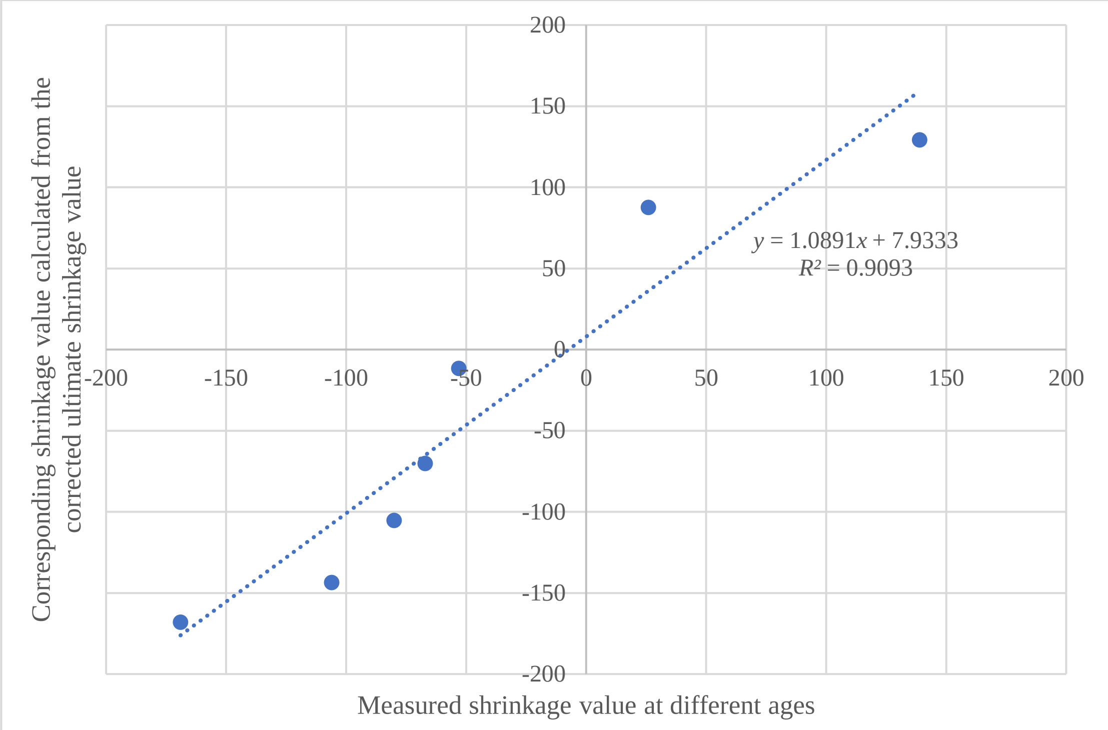

Figure 5.23 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 35/0/0/65

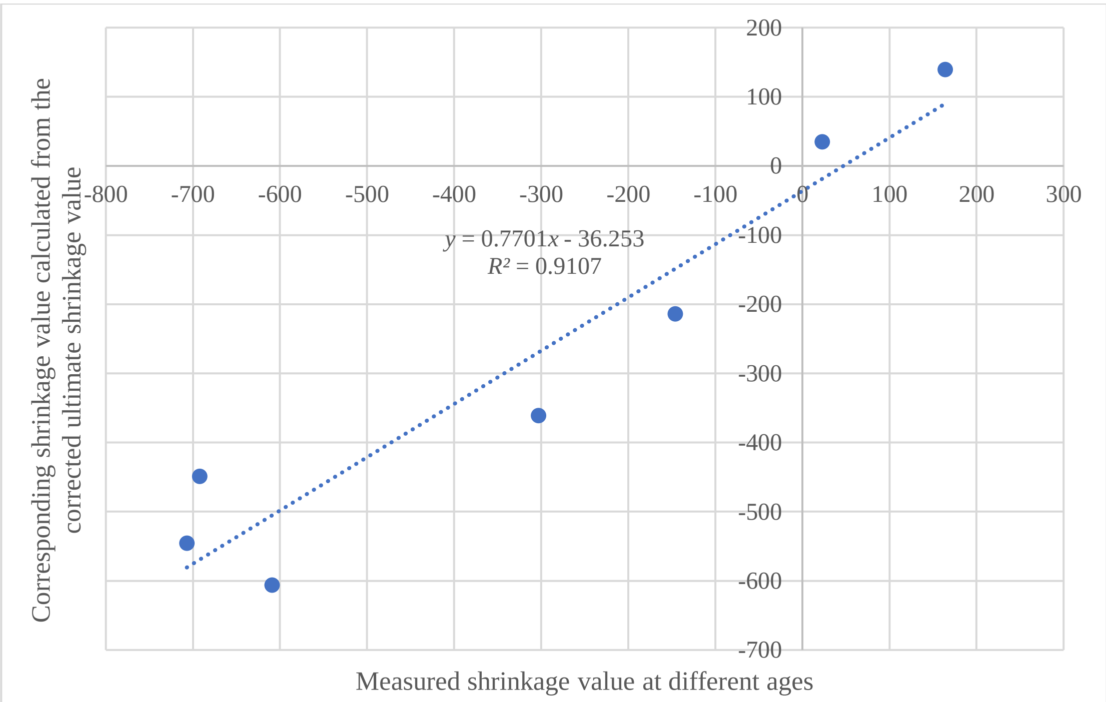

Figure 5.24 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 32.5/32.5/0/35

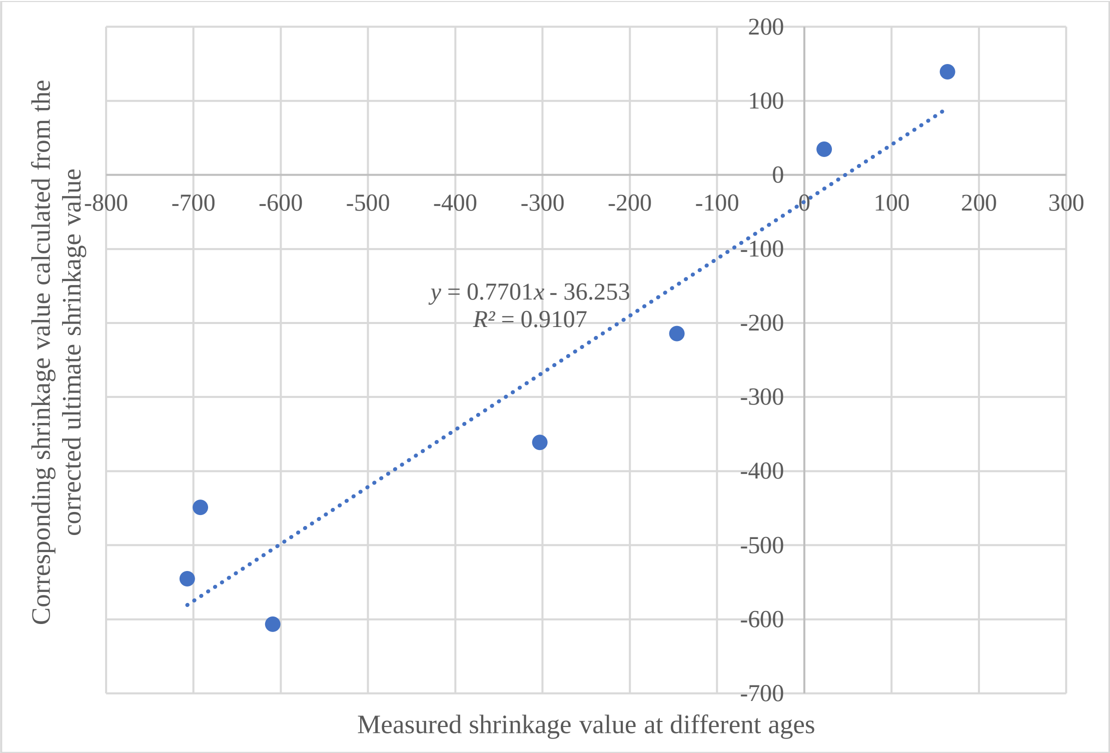

Figure 5.25 Correlation between the measured shrinkage values and corresponding calculated shrinkage values/corrected ultimate shrinkage values at different ages for concrete formed from mix 17.5/17.5/0/65

Chapter 6 Fire Resistance Performances of Concretes Containing Combinations of CSAC, OPC, PFA and GGBS Binders

6.1 Introduction

The use of concrete structural members in buildings is subject to the fire safety requirements stipulated in design codes [14, 48]. Fire is considered one of the most harmful conditions to which concrete may be exposed, and such exposure may result in strength reduction, spalling or, in the most severe scenario, a collapse failure. In this regard, fire resistance ratings and the effects of elevated temperature on the mechanical properties of concrete must be examined during the design stage to determine the safety of a structural member or an entire building exposed to such conditions. Fire resistance ratings of concrete are typically formulated in terms of the structural design parameters, such as the concrete strength and reinforcement covering, and were not explored in this study. Instead, this study focuses on determining the extent to which the compressive strength of concrete is reduced by exposure to an elevated temperature of 300°C, which is the common fire level investigated in many previous studies [32, 50, 51].

The change in the compressive strength of concrete under elevated temperatures has been examined extensively in previous studies [31, 32, 50, 51]; however, these primarily evaluated concretes containing OPC binder alone or in combination with PFA binder. In addition, the fire-resistant properties of normal-strength concrete and high-strength concrete differ, as mentioned by Kodur & Harmanthy [50], and the latter were not explored in this study. In both the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] (Hong Kong Design Code) and BS EN 1992-1-2: 2004 (Design of concrete structures – Part 1-2: General rules – Structural fire design) [48], the nominal strength reduction factors of concrete exposed to different levels of elevated temperatures are given. However, the latter provides a set of data for concretes containing siliceous aggregates and a set for concretes containing calcareous aggregates, whereas the former provides a single set of data. In this study, as the aggregates used in the concretes were granitic in nature, the strength reduction factors for concretes containing siliceous aggregates are used. Kodur [51] first observed a noticeable effect on the compressive strength of concretes in the exposure-temperature range of 200 - 400°C, and this effect rapidly became more marked as the temperature increased further. Therefore, in this study, the middle temperature in that range, i.e., 300°C, was chosen as the temperature at which to perform preliminary evaluations of the fire-resistant properties of concretes containing various combinations of binders.

The examination of the strength reduction properties of concretes incorporating CSAC binder was conducted to yield values for comparison with those given in the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] and the BS EN 1363-1 (Fire resistance tests Part 1: General Requirements) [52]. Two sets of concrete cube specimens were prepared from each of the concrete mixes containing various binder combinations (i.e., two cubes of each concrete type were prepared) and were cured in accordance with Hong Kong Construction Standard 1: 2010 [30] for 28 days. One set of cubes was tested to determine the normal 28-day compressive strength, and the other set was heated to 300 ± 10°C at a rate of 20°C per minute and maintained at this peak temperature for 2 h prior to determination of the 28-day compressive strength.

Due to the limitations of the furnace used for heating, the rate of temperature increase did not follow the standard fire curve stated in BS EN 1363-1 (Fire resistance tests Part 1: General Requirements) [52]. Nevertheless, the equipment was considered to be adequate for collecting preliminary data on the fire-resistant properties of CSAC concretes, in terms of their resistance to loss of compressive strength. The compressive strengths of the test cubes with and without exposure to 300°C are compared. The strength reduction factors are calculated by dividing the compressive strengths of cubes that had been exposed to 300°C by those of cubes that had been cured normally. The strength reduction factors are then compared with the nominal strength reduction factors given in the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] and the BS EN 1363-1 (Fire resistance tests Part 1: General Requirements for Fire Structural Design) [52]. The results of this comparison are then used to compare the fire-resistant properties of concretes containing the studied combinations of binders to those of concretes containing combinations of ordinary binders, which are normally stated in design codes.

6.2 Research significance

The fire resistance of concrete is a critical parameter in the structural design of concrete structures and is addressed in all design codes, as it affects the safety of buildings exposed to various extents of fire. There are stringent requirements for the minimum coverage of reinforced concrete members in all design codes to ensure the durability of steel reinforcements and prevent concrete spalling during building fires. In addition, estimates of reductions in the compressive strength of concretes exposed to various levels of elevated temperature are given. Again, however, these strength reduction factors were established for concretes containing only OPC binder, and their applicability to concretes containing combinations of other binders is uncertain.

Thus, the commonly used elevated temperature level (i.e., 300°C) was chosen to experimentally examine the applicability of the strength reduction factors given in the Hong Kong design code [14]. The results of this study will help structural engineers to obtain more accurate estimations of the fire-induced reduction in strength of concretes containing binders other than OPC, particularly those that contain CSAC in combination with other binders.

6.3 Methodology

As elaborated in Chapter 3, two standard 100-mm^3 test specimens were cast from each of twenty concrete mixes containing various combinations of binders, as listed in Table 3.2, and were tested in accordance with the procedure given in Table 3.3. Thus, the test specimens were first cured under standard curing conditions in accordance with Construction Standard 1: 2010 [30] for 28 days. At this time, the compressive strength of one set of specimens was measured, while the other was heated to 300°C for 2 h at a heating rate of 20°C per minute, cooled to room temperature and subjected to compressive strength measurement.

The compressive strengths of specimens of each of the twenty concretes with and without exposure to 300°C are compared, and the strength reduction factors for exposure to 300°C are calculated by dividing the compressive strengths of specimens exposed to 300°C by those of specimens subject to curing only. These strength reduction factors are then analysed.

6.4 Test results and discussions

The compressive strengths of the specimens that were and were not exposed to a temperature of 300°C for 2 h are listed in Table 6.1 together with their respective strength reduction factors, which are the quotients of the compressive strengths with and without heating. The calculated strength reduction factors are plotted against the percentages of CSAC binder in each concrete, as shown in Figure 6.1.

The correlation curve in Figure 6.1 shows a linear relationship between the strength reduction factors of concretes with the same water-to-binder ratio and the percentage of CSAC in the binder combination. Specifically, the strength reduction factor decreases as the percentage of CSAC in the binder combination increases. The coefficient of determination of 0.8715 confirms the high credibility of this linear relationship. This phenomenon is due to ettringite crystals formed in the hydration of CSAC. Although ettringite crystals contribute to strength development at early age, they are vulnerable to degradation when exposed to elevated temperatures. Consequently, compressive strength of concrete reduces with the reduction rate proportional to the quantity of ettringite crystals present, which is dependent on the amount of CSAC in the binder combination.

6.5 Establishment of a predictive model for the strength reduction factors of concretes incorporating CSAC in their binder combinations

The concretes formed from the three mixes that did not contain CSAC in their binder, i.e., mixes 0/100/0/0, 0/75/25/0 and 0/65/35/0, had strength reduction factors of 0.83, 0.89 and 0.84 respectively, which are in line with the strength reduction factor of 0.85 given in Table 3.5 of the Hong Kong Code of Practice for Structural Use of Concrete 2013 [14] and Table 3.1 of the BS EN 1992-1-2: 2004 ("Design of Concrete Structures – Part 1-2: General rules – Structural fire design") [48] for concrete containing siliceous aggregates that is exposed to a temperature of 300°C. Thus, despite the different rate of increase in temperature used in this study from that used in the standard fire cure mentioned in the above codes, these study results are considered to be valid.

The correlation equation given in Figure 6.1 can be represented as:

$$SRF_{300} = 0.8336 – 0.6934P_{CSAC} \qquad \text{(Eq. 6.1)}$$

where SRF_{300} = the strength reduction factor of a concrete exposed to a temperature of 300°C and P_{CSAC} = the percentage of CSAC binder in a concrete mix containing OPC and other supplementary binder materials (PFA and GGBS).

Equation 6.1 shows that when the percentage of CSAC is zero, the strength reduction factor becomes a constant that represents the strength reduction factor for concretes containing ordinary binder combinations, without CSAC. The strength reduction factor of 0.85 for the exposure condition of 300°C, as listed in both design codes [14, 48], is very close to the constant in Equation 6.1. As such, Eq. 6.1 can be rewritten as:

$$SRF_{300} = 0.85 – 0.7P_{CSAC} \qquad \text{(Eq. 6.2)}$$

The strength reduction factors for different concretes are calculated using Eq. 6.2, based on the percentage of CSAC in the concrete mixes from which they were formed. From Eq. 6.2, it can be seen that the strength reduction factors for concretes are inversely proportional to the % of CSAC in the binder combination. When there is no CSAC present, the strength reduction factor is 0.85, which is the same figure given in the design codes [14, 52]. The test-to-prediction ratios of the measured strength correction factors to the correction factors predicted from Eq. 6.2 are calculated and are shown in Table 6.1. The mean, standard deviation and coefficient of variation of these values are 0.98, 0.15 and 15%, respectively. The closeness of the mean to 1 illustrates the similarity of the measured and predicted values. Similarly, the 15% coefficient of variation also indicates the relatively small variations of the data from the mean. These statistical results confirm that the equation given in Eq. 6.2 can generate a reasonable prediction of the strength reduction factor of a concrete exposed to a temperature of 300°C with respect to the percentage of CSAC in its binder combination. Accordingly, it should be possible to derive equations, verify these by analogous experimental approaches and calculate the strength reduction factors for concretes exposed to other elevated temperatures.

6.6 Conclusions and limitations

The strength reduction factors obtained for concretes without CSAC binder that were exposed to a temperature of 300°C are generally in good agreement with those given in design codes [14, 48]. As the percentage of CSAC in the mix increases, the strength reduction factor of the resulting concrete decreases after exposure to a temperature of 300°C. This proves that the weakening of concrete at 300°C is due to the degradation of ettringite crystals, which are formed during the early hydration of CSAC binder. Therefore, concretes that incorporate CSAC in their binder combinations are more vulnerable to strength reductions after exposure to elevated temperatures at which the crystal structure of ettringite is damaged. Furthermore, the deterioration or decomposition of ettringite crystals leads to a decrease in the compressive strength of a concrete that is proportional to the quantity of ettringite crystals present, which is, in turn, proportional to the quantity of CSAC binder in the concrete. It can therefore be concluded that the greater the percentage of CSAC in the binder combination of a concrete, the greater the reduction in its strength after exposure to elevated temperatures that degrade ettringite crystals.

As only one temperature (300°C) was selected for investigation, the results obtained in this study represent a preliminary examination of the fire-resistant properties of concretes that incorporate CSAC in their binder combinations. To obtain a comprehensive view of the fire-resistant properties of concrete incorporating different percentages of CSAC binder, the author intends to conduct further tests at different elevated temperatures. This will enable the determination of the strength reduction factors for CSAC concretes exposed to different elevated temperatures.

Although the furnace used for heating was not able to reproduce the heating profile of the standard fire curve given in BS EN 1363-1 (Fire resistance tests Part 1: General Requirements) [52], the strength reduction factors determined from the test results obtained at 300°C are in reasonable agreement with those given in the current design codes [14, 48]. There is little difference between the test-to-prediction ratios of the strength reduction factors obtained from the actual experimental results of the test specimens and the values predicted using Eq. 6.2. This shows that the relationship derived in Eq. 6.2 affords reasonable predictions of the strength reduction factors of concrete specimens after exposure to a temperature of 300°C, wherein these concretes incorporate various percentages of CSAC in their binder combinations. Moreover, concretes that contain CSAC in their binder combinations have poorer fire-resistant properties than those of OPC concrete, as exhibited by the greater strength reduction in the former after exposure to a temperature of 300°C.

In addition, experimental results obtained in this study show that strength reduction is inversely proportional to the % of CSAC in the binder combination. This is believed to be related to the temperature instability of ettringite crystals formed in the early hydration process of CSAC. Based on this, more vigorous reduction in strength for concretes containing CSAC under higher temperature (> 300^{o}C) or prolonged exposure (>2 hours) can be envisaged. Designers and materials engineers should be cognisant of the possible fire safety risks of CSAC as a binder in concrete, particularly for indoor structural elements.

This study only examined concretes with CSAC percentages in their binder combinations within a certain range after exposure to a single elevated temperature. Therefore, the results are preliminary, and the applicability of the derived predictive equation is limited. To fully explore the fire-resistant properties of concretes that contain CSAC binder and to derive their corresponding strength reduction factors across the full range of elevated temperatures given in current design codes [14, 48], further studies are necessary.

Accordingly, as an extension of this study, analogous experimental processes have been planned to verify the applicability of Eq. 6.2 to concretes that contain different percentages of CSAC binder and are exposed to a variety of elevated temperatures. The results of this proposed study will be compared with the strength reduction factors at a variety of elevated temperature levels that are given in current design codes for concretes that contain ordinary binder materials. If successful, this will allow the strength reduction factors (SRF_X) to be obtained for concretes that incorporate various percentages of CSAC binder (P_{CSAC}) and are exposed to elevated temperature level X.

Table 6.1 Twenty-eight-day compressive strengths of concretes formed from various mixes and with and without 2-h exposure to 300°C, and comparison of strength reduction factors from design codes/calculations

Mix ID	Proportion of CSAC	28-day compressive strength test result (MPa)		Strength reduction factor (0.85 as given in design codes)		
		Exposure to 300°C for 2-h		test results	Calculated results from Eq. 6.2	Ratio of test results to calculated results
		No	Yes			
100/0/0/0	100%	55.6	9.4	0.17	0.15	1.13
75/25/0/0	75%	54.5	20.2	0.37	0.33	1.12
50/50/0/0	50%	57.0	29.1	0.51	0.50	1.02
25/75/0/0	25%	58.6	34.5	0.59	0.68	0.87
75/0/25/0	75%	36.5	11.2	0.41	0.33	1.24
65/0/35/0	65%	27.0	10.3	0.38	0.40	0.95
55/0/45/0	55%	23.3	7.9	0.34	0.47	0.72
0/100/0/0	0%	58.7	48.5	0.83	0.85	0.98
37.5/37.5/25/0	37.5%	48.9	31.3	0.64	0.59	1.08
32.5/32.5/35/0	32.5%	44.0	32.3	0.73	0.63	1.16
27.5/27.5/45/0	27.5%	39.8	29.9	0.75	0.66	1.14
0/75/25/0	0%	48.3	42.8	0.89	0.85	1.05
0/65/35/0	0%	44.5	37.2	0.84	0.85	0.99
5/95/0/0	5%	55.9	41.1	0.74	0.82	0.90
70/5/25/0	70%	37.4	11.9	0.31	0.36	0.86
65/10/25/0	65%	39.1	13.1	0.34	0.40	0.85
65/0/0/35	65%	41.8	13.4	0.32	0.40	0.80
35/0/0/65	35%	31.7	13.2	0.42	0.61	0.69
32.5/32.5/0/35	32.5%	51.3	27.7	0.54	0.62	0.87
17.5/17.5/0/65	17.5%	40.1	31.4	0.78	0.73	1.07
Mean						0.98
Standard deviation						0.15
Coefficient of variation						15%

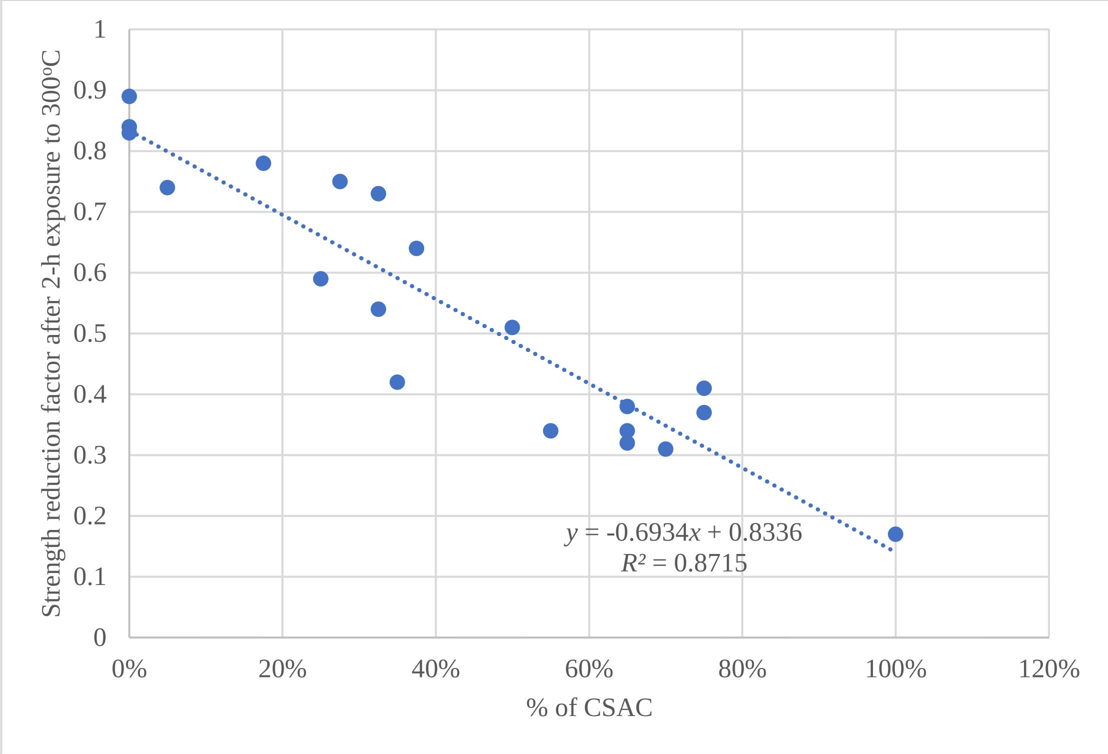

Figure 6.1 Relationship between the percentage of CSAC in concrete mix and the strength reduction factor of the corresponding concrete after 2-h exposure to 300°C

Chapter 7 Summary and conclusions

7.1 Summary

Three key properties of concretes that contain various combinations of CSAC, OPC, PFA and GGBS binders were studied in this work, namely the short-term to long-term strength development, ultimate shrinkage value and fire resistance in terms of the strength reduction factor after exposure to a temperature of 300°C. Concretes containing binder combinations that incorporated CSAC performed differently from ordinary concretes that contained OPC binder alone or in combination with PFA and GGBS binder. Specifically, the concrete specimens containing CSAC in their binder combinations, either alone or blended with other binders, exhibited characteristics of strength development at very early ages that were superior to those of non-CSAC concretes. CSAC is chosen as the key binder material in concrete mainly for this characteristic, as it allows an earlier opening for service of the concrete structure of interest. Furthermore, the long-term strength performance of the concrete specimens was not adversely affected by the presence of CSAC in the binder combination, except when the binders comprised only CSAC blended with PFA. This suggests that the pozzolanic properties of PFA, which are necessary for its contribution to strength, are not activated in the absence of $Ca(OH)_2$, as this is generated by the hydration process of OPC but not that of CSAC.

Although economic and environmental concerns have led to an increasing demand for CSAC in multiple binder combinations for concretes, there has been little exploration of the properties of these concretes, such as their compressive strength development trends and ultimate shrinkage. This study yielded experimental results that concur with findings from previous studies: concrete formed from a mix containing pure CSAC binder exhibited good early strength development within 2–6 h and a 28-day strength comparable to that of pure OPC concrete. In addition, the test results obtained for pure CSAC concrete at later ages (up to 365 days) were similar to those of pure OPC concrete. In contrast, combinations of CSAC and PFA binder formed weaker concretes, as CSAC seemed to not have the same reactivity as OPC, mainly because the hydration of the former does not producing $Ca(OH)_2$, which is needed to activate the pozzolanic properties of PFA and enable its contribution to strength. Nevertheless, a small percentage (5%) of OPC in a binder combination was sufficient to restore the strength contribution of PFA at later ages (up to 365 days), and a higher percentage of OPC in the binder combination appeared to increase the speed of PFA-mediated strength development. However, unlike PFA, GGBS has its own strength-contributing ability, and concretes containing binder combinations of GGBS and CSAC exhibited similar strength levels at later ages (up to 365 days) even in the absence of OPC, although the presence of OPC apparently increased the rate of strength development at earlier ages.

The findings regarding the development of shrinkage in concretes containing different combinations of CSAC, OPC, PFA and GGBS binders preliminarily confirm that the generally acknowledged contributions of both PFA and GGBS binder to the reduction of concrete shrinkage do not persist at ages beyond 28 days. Specifically, the shrinkage measurements of concrete specimens incorporating PFA or GGBS binders were continued up to the age of 365 days, and show that these binders delayed rather than reduced concrete shrinkage. In addition to confirming previous findings on the proportional relationship of concrete shrinkage to compressive strength, the manner in which concrete shrinkage development is determined by its binder combinations was explored. Based on the experimental results and explorations of the relationship between shrinkage development and the binder combinations of each concrete examined in this study, the commonly used predictive model for concrete shrinkage is now furnished with new correction factors for CSAC, OPC, PFA and GGBS binders. This will ensure the applicability of the predictive model to concretes containing a much broader range of combinations of these four binders.

The above achievements regarding the prediction of the compressive strength and shrinkage performance of concretes will substantially reduce the time required for conducting trials to confirm the mix designs to be used for concretes in a project or for cost estimation at the design stage. However, it must be noted that the use of binders sourced from different suppliers or areas may lead to concretes that exhibit slightly different mechanical strengths and ultimate shrinkage performance to those previously obtained, even if the materials are of the same class or grade as the binder that was previously used successfully. It is therefore advisable to validate the prediction models for a group of supplied binders, such as CSAC, OPC, PFA and GGBS, depending on which are to be incorporated into the binder combinations of concretes for practical use. These validations can be performed by analysing the results obtained from initial trials of mechanical strengths and shrinkage values ranging from early ages of a few hours up to 28 days, or any later age that is practically acceptable.

A preliminary study was also made of the fire-resistant properties of concretes that contained various percentages of CSAC in their binder combinations, in terms of their strength reduction factors after exposure to a temperature of 300°C. This is considered the temperature at which a measurable effect on the compressive strength of a concrete should be apparent [50, 51]. The strength reduction factor of concretes decreased under this condition as the CSAC binder content increased, and this observation is used to derive an empirical equation for predicting the strength reduction factors of a concrete exposed to a temperature of 300°C, with respect to the percentage of CSAC in the binder combination.

7.2 Conclusions

The following conclusions can be drawn from the results obtained in this study.

(a) CSAC binders lead to rapid strength development and volume stability in concretes at early ages up to the result of 34.7 MPa in 6 hours obtained in this study with 420 kg of CSAC per m^3 of concrete.

(b) Notwithstanding the early age strength performance, pure CSAC concrete is able to achieve 95% and 92% ($SF_{CSAC-28} = 0.95$ & $SF_{CSAC-365} = 0.92$) of the compressive strength of pure OPC concrete at 28 days and 365 days respectively.

(c) It was found that small % (5 – 10%) of OPC in the concrete mix are already adequate to activate the pozzolanic reaction of PFA that leads to strength development. PFA concretes with small % of OPC are able to achieve similar compressive strength as those with higher OPC contents at 365 days, albeit the development pace is slower.

(d) Compressive-strength prediction equations (Eqs. 4.2, 4.4 and 4.5) are derived to predict the early-age (2–6 h), 28-day and 365-day compressive strength performances of concretes that contain various binder combinations. Different strength factors are derived for each of the CSAC, OPC, PFA and GGBS binders.

(e) PFA gives negative contribution to strength development at 28 days and 365 days in the absence of OPC ($SF_{PFA\text{-}28}$ = -0.36; $SF_{PFA\text{-}365}$ = -0.32). Unlike PFA, GGBS is able contribute to strength development at 28 days and 365 days in the absence of OPC ($SF_{GGBS\text{-}28}$ = 0.3; $SF_{GGBS\text{-}365}$ = 0.6).

(f) When OPC is incorporated into a binder combination, pozzolanic reactions of both PFA and GGBS are activated to give strength contribution with higher strength factors ($SF_{PFA\text{-}28}$ = 0.36; $SF_{PFA\text{-}365}$ = 0.95; $SF_{GGBS\text{-}28}$ = 0.6; $SF_{GGBS\text{-}365}$ = 0.77).

(g) Concretes containing CSAC exhibit lower shrinkage at both early and late ages than those containing OPC.

(h) Predictive equation for estimating ultimate shrinkage of concretes with different binder combinations is derived based on the GL2000 model given in ACI 209.2R-08 [15] with shrinkage correction factors established for each binder material (K_{CSAC} = 0.29; K_{OPC} = 1; K_{PFA} = 0.05; $K_{PFA\text{-}OPC}$ = 1.0; K_{GGBS} = 0.07; $K_{CSAC\text{-}OPC}$ = 1.0).

(i) Strength reduction factor at 300^{o}C, which is an indicator for fire resistance properties, of concrete is found to be inversely proportional to the % of CSAC in the binder combination. A linear equation is derived for estimating the strength reduction factors of concretes with different CSAC content at 300^{o}C.

Chapter 8 Limitations of Study and Recommendations for Future Studies

8.1 Limitations to the use of concretes with incorporated CSAC binder

This study verifies the many benefits of using CSAC as a binder in concretes, in comparison to the use of OPC. Nevertheless, the unique hydration mechanism of CSAC means that its characteristics differ from those of OPC, and thus CSAC is not widely favoured for use a concrete binder by most designers or structural or materials engineers. In particular, the rapid setting and early strength properties of CSAC concretes require the addition of a suitable dosage of a compatible retarding agent to extend the workable time to suit different on-site casting methods. In this regard, knowledge of the properties of fresh CSAC concrete is needed to assist concrete engineers to develop mix designs and binder combinations that are practically applicable.

The fire resistance of concrete, in terms of its strength reduction after exposure to elevated temperatures, is another major concern when using concretes incorporating CSAC binder in building works. In this study, the strengths of concretes incorporating CSAC binder were reduced to a greater extent than those of ordinary OPC concretes when exposed to a temperature of 300°C, which is equivalent to a medium fire-exposure condition. CSAC concrete is therefore not suitable for use in casting entire structural elements for building works, particularly those for use in indoor environments. However, it may be acceptable to use CSAC concretes to repair relatively small portions of a structural element. This is consistent with the current real-life applications of CSAC concretes, which are generally used either alone or in combination with other binder materials for the repair of concrete bridges and carriageways.

8.2 Limitations of the study test methods and suggestions for future work

The properties of concretes depend on many parameters, such as the binder combination, total binder content and water-to-binder ratio. This study used the most commonly used design parameters for grade 45 concretes, namely a water-to-binder ratio of 0.42, a total binder content of 420 kg/m^3 and the most commonly adopted percentages of each binder. Further verification of the applicability of the equations and factors derived in this study to concretes with other water-to-binder ratios or total binder contents may be required. In particular, it is recommended to use the same or similar test regimes to study concretes of other strength grades, particularly those of high-strength (grade 60 or above). The obtained results will be useful for deriving equations that can predict the structural properties of concretes formed from a wider range of commonly used concrete mixes.

The examination of the fire-resistant properties of concretes containing different percentages of CSAC in their binders, in terms of their strength reduction factors, was performed using only elevated one temperature (300°C), which was considered in previous studies to be a medium-level elevated temperature under fire [50, 51]. Nevertheless, further studies involving higher possible elevated temperatures are recommended, as these will enable the derivation of more strength reduction factors for comparison with those given in current design codes [14, 48] for the same elevated temperatures. This will enable the further development of strength reduction factors for CSAC concretes across the full range of elevated temperatures given in the current design codes [14, 48], and in turn will furnish a comprehensive set of the major design parameters, including the compressive strength and shrinkage, of these novel concretes.

In many previous studies [2 - 5], scanning electronic microscopy (SEM) has been used to study the microstructures of ettringite crystals in concretes that contain CSAC as a binder. Although SEM was not included in the test plan of this study, the observed larger reduction in the strengths of CSAC concretes compared to those of OPC concretes after exposure to an elevated temperature suggests that directly viewing changes in the microstructures of ettringite crystals may be an interesting topic for future exploration. It is therefore recommended that in future work, SEM should be used to capture images of CSAC concretes at a range of elevated temperatures, and changes in the microstructures of ettringite crystals should be determined under these conditions.

8.3 Future development of CSAC concrete

Cement has been used for thousands of years, and the modern use of OPC as a concrete binder has developed over the past hundred or more years. Accordingly, its properties have been extensively studied. The combined use of OPC with supplementary binder materials, such as PFA, GGBS and rarer examples, has also been investigated for decades.

In contrast, CSAC is a relatively “young” binder that was invented in the 1960s for military use. Its real-life applications have broadened only in the past 30 years, due to its decreasing production cost and its advantages over OPC. However, the accumulated knowledge on the use of CSAC in concrete is much less than what is known about OPC concretes. In this regard, there is a need for more research on the properties of CSAC in concretes, such that it can be used as commonly as OPC as a binder in concretes. Notably, the rapid strength development of CSAC concretes renders them well suited for shortening the production cycle of modular integrated construction units, provided that the fire resistance of these concretes can be improved.

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