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Technical report

Model for predicting shrinkage of concrete using calcium sulfoaluminate cement blended with OPC, PFA and GGBS

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Abstract

Shrinkage is an important concern in concrete since it induces deformation and tensile stress, which may finally lead to cracking, in structural concrete members. Prediction for shrinkage of concrete is therefore an essential step at the structural design stage for determining required preventive measures. Following this need, various models are developed for predicting shrinkage of concrete in design codes. Unfortunately, their common shortcoming is the limited applicability to common cement types only. Lately in concrete repair applications, Calcium Sulfoaluminate Cement (CSAC) is becoming more and more popularly used due to its well-known properties of rapid strength gain and relatively low shrinkage. Nonetheless, since little study has been done for its long term shrinkage performance beyond the age of 28 days or even 56 days, the previously developed shrinkage prediction models are not applicable for concrete incorporating CSAC, not to mention when it is blended with other binder materials such as Ordinary Portland Cement (OPC), Pulversized Fuel Ash (PFA) and Ground Granulated Blastfurnace Slag (GGBS).

In this study, shrinkage measurements were conducted for a total of 20 concrete mixes with different binder combinations but the same total binder content of 420 kg/cum of concrete and the same water to binder ratio of 0.45 for observing their shrinkage development trends at different ages up to 1 year.

The GL2000 Model for shrinkage prediction given in ACI 209.2R-08 is adopted for comparing with the measured results. Different k factors to be put in the GL2000 Model for different binder materials are derived and verified with the shrinkage results.

Key Words: Calcium Sulfoaluminate Cement (CSAC); Ordinary Portland Cement (OPC); Pulverized Fuel Ash (PFA); Ground Granulated Blasfurnace Slag (GGBS); Binder materials; Early ettringite formation; Strength Development Trend, shrinkage development trend

Abbreviation & Symbols

CSAC: Calcium Sulfoaluminate Cement
OPC: Ordinary Portland Cement

PFA:	Pulversized Fuel Ash
GGBS:	Ground Granulated Blastfurnace Slag
ε_{shu}:	Ultimate shrinkage strain
$\varepsilon_{t:}$	Shrinkage strain at time t
ε_{sh-365}:	Shrinkage strain at 365 days
t:	time in days since the end of moist curing
k_b:	k factor for binder b in GL2000 Model
k_{bc}:	Combined k factor for a certain binder combination in GL2000 Model
$\%_b$:	% of binder material b in a certain binder combination used in concrete
k_{csac}:	k factor for CSAC with absence of OPC in GL2000 Model
$k_{csac-opc}$:	k factor for CSAC with presence of OPC in GL2000 Model
k_{opc}:	k factor for OPC in GL2000 Model
k_{pfa}:	k factor for PFA with absence of OPC in GL2000 Model
$k_{pfa-opc}$:	k factor for PFA with presence of OPC in GL2000 Model
k_{ggbs}:	k factor for GGBS with absence of OPC in GL2000 Model
$k_{ggbs-opc}$:	k factor for GGBS with presence of OPC in GL2000 Model
$k_{csac/opc:}$	Combined k factor for CSAC/OPC blend in GL2000 Model
$k_{csac/opc/pfa:}$	Combined k factor for CSAC/OPC/PFA blend in GL2000 Model
$k_{opc/pfa:}$	Combined k factor for OPC/PFA blend in GL2000 Model
$k_{csac/ggbs}$:	Combined k factor for CSAC/GGBS blend in GL2000 Model
$k_{csac/opc/ggbs}$:	Combined k factor for CSAC/OPC/GGBS blend in GL2000 Model

1. INTRODUCTION OF STUDY

Calcium Sulfoaluminate Cement (CSAC) has become a commonly used binder in concrete or mortar for concrete repair applications due to its beneficial properties of rapid growth in strength and volume stability. CSAC is mostly used alone as the sole binder material for concrete in the past but blending with Ordinary Portland Cement (OPC), Pulverized Fuel Ash (PFA) or Ground Granulated Blastfurnace Slag (GGBS) is the latest trend especially when the demand for early strength development is not too stringent [1]. On the other hand, although CSAC is already a lower carbon bearer than OPC [1], replacement of these key binder materials with PFA and GGBS can further reduce the total carbon footprint of the resulted concrete.

Shrinkage is in general defined as the volume reduction of concrete when being subject to loss of moisture through migration to the environment and internal consumption in hydration process [2]. Apart from the key properties of compressive strength, shrinkage is also an important parameter in structural consideration since excessive shrinkage may lead to subsequent problems in concrete members such as possibility of cracking, excessive deformation or prestress loss, in the case of prestressed concrete [2]. By the same token, excessive shrinkage may also induce excessive shear bond stress in concrete repair works at interfaces of concrete repair works thus causing detachment of the repair concrete/mortar from parent concrete. Both ACI 318R-14 "Building Code Requirements for Structural Concrete" [3] and BS EN 1992-1-1:2004+A1:2014 – "Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings" [4] state that shrinkage, other than creep and temperature effects, has to be considered in controlling cracks or structural failure. Shrinkage is also one of the important parameters in structural design for determining design loads and provision of shrinkage resistant reinforcement at appropriate locations of a structure is often in need [3,4].

CSAC is well-known of its volume stability, which is realized by its early formation of expansive ettringite crystals to compensate subsequent drying shrinkage [5,6].

Nevertheless, commonly used shrinkage test methods only require measurements up to the age of 28 days or even up to 56 days [7]. Consideration for ultimate shrinkage performance of concrete may sometimes be misled if its shrinkage development is just delayed but not actually permanently reduced. If this is the case, shrinkage may continue to develop and ultimately reach the same or similar magnitude as that of ordinary concretes not using CSAC.

In previous study [7], it was found that concrete with different binder combinations of CSAC, OPC, PFA and GGBS would result in different strength development trends due to the inter-alteration of the hydration mechanism among the binders. It has also been proved in the same study [7] that the hydration mechanisms of PFA and GGBS are different with or without the presence of OPC in the binder combination. As such, shrinkage development trend of concrete, at least for the part of autogenous shrinkage, can also be expected to be sensitive to the hydration mechanism. In this regard, strength development trends of the concrete mixes obtained in previous study [7] is also reviewed in this study for analyzing the shrinkage development trends of the same concrete mixes. Since shrinkage is an important parameter in structural engineering design and therefore prediction of long-term shrinkage at the structural design stage is also required in design codes such as ACI 318R-14 [3] and BS EN 1992-1-1:2004+A1:2014 [4]. Nevertheless, shrinkage prediction models in design codes for concretes is limited to ordinary binder materials but not special cements like CSAC and its combinations with OPC, PFA or GGBS. Taking ACI 209.2R-08 [8], which is referred in ACI 318R-14 [3], only Ordinary Portland Cement, Sulfate Resistant Cement and Rapid Hardening Cement are covered. Hence, CSAC and its other binder combinations is not covered in the prediction model therein. Shrinkage prediction model for concretes with these binder combinations is therefore in need. Prediction approach based on the GL2000 Model as described in ACI 209.2R-08 [8] is adopted in this study.

2. RESEARCH SIGNIFICANCE

This study aims to derive suitable k factors to be put in the GL2000 Model given in ACI 209.2R-08 [8] for predicting shrinkage performance of concretes using different binder combinations with CSAC other than those common cement types already covered. Shrinkage performance of concrete mixes are measured up to the age of 365 days, when the fluctuation in shrinkage development trends due to interaction among binder materials are expected to have become stable enough for calculating the ultimate shrinkage values.

In ACI 209.2R-08 [8], several models are given for estimating the shrinkage performance of concrete. Among the models given, the widely adopted GL2000 Model is chosen in this study for comparing with the ultimate shrinkage values calculated from the 365-day shrinkage values measured in this study. Since the calculation factors (k factors) for shrinkage performance characteristics are only given in this model for cement types I, II & III classified in ASTM C150-07 “Standard Specification for Portland Cement” [9] for ordinary Portland cement, moderate sulfate resistant cement and high early strength cement respectively. It has been explicitly mentioned in ACI 209.2R-08 [8] that the models given there were developed for concretes with typical compositions with the specified cement types and further calibration should be done to the models by testing concrete with other binder compositions [8].

New k factors are then established and put in the GL2000 Model to predict the ultimate shrinkage values for comparing with the calculated ultimate shrinkage value. If deviations between predicted values and calculated values are within ±20%, which is the acceptable range suggested in ACI 209.2R-08 [8], the established k factors are deemed able to give predicted values in proximity of the actual ultimate shrinkage values. Furthermore, all the predicted values and calculated values from all the 20 concrete mixes are then plotted in linear graph for evaluating the overall confidence level for the replicability of the derived prediction model by checking the coefficient of determination of the linear graph.

Significance of the established k factors for concrete with binder combinations of CSAC, OPC, PFA and GGBS is to enable prediction of shrinkage performance of these concretes, which is required in structural engineering design.

3. MATERIALS AND METHODOLOGIES

CSAC manufactured by CTS Cement Corporation complying to GB/T 20472: 2006 "Sulphoaluminate cement" [10] was used in this study. The CSAC contains 80% of CSAC clinker, which is composed of 58% ye'elimite ($C_4A_3\hat{S}$, where C, A & $\hat{S}$ represents CaO, Al_2O_3, SO_3 respectively), 12% belite, 20% anhydrous calcium sulfate as well as other minor ingredients. The OPC used is China Resources Brand Class 52.5N Type CEM1 conforming to BS EN 197-1: 2000 "Cement. Composition, specifications and conformity criteria for common cements" [11]. For supplementary binder materials, PFA (also known as fly ash) conforming to BS EN 450-1:2012: "Fly ash for concrete. Definition, specifications and conformity criteria" [12] is from Hong Kong China Light & Power Co., Ltd. and GGBS conforming to BS EN 15167-1:2006: "Ground granulated blast furnace slag for use in concrete, mortar and grout. Definitions, specifications and conformity criteria" [13] is supplied by Hong Kong K-Wah Building Materials Co., Ltd. Key ingredients of the binder materials used in this study are summarized in Table 1. Twenty mixes of different combinations of binder materials of CSAC, OPC, PFA and GGBS with the same water binder ratio of 0.45 and total binder content of 420 kg are included in this study as shown in Table 2. The target workability of 150 mm ± 25 mm slump was achieved by adding high range water reducing agent (Master Glenium SP8S ex BASF). Due to the fast setting properties of CSAC, stabilizing agent (Delvocrete ex BASF) was used to prolong the workability retention time of concretes containing CSAC to ensure adequate placing time. Dosages of Delvocrete, which are slightly different for concretes with different CSAC contents, are listed in Table 2. Concrete mixes are named with their percentage combinations of CSAC, OPC, PFA and GGBS in sequence (e.g. 0/75/25/0 denotes binder combination of 0% of CSAC, 75% of OPC, 25% of PFA and 0% of GGBS). Test specimens were cast in accordance with ASTM C157/C157M – 08 (2014): "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" [14] for shrinkage measurement. Three 75 mm square prisms of approximately 285 mm in length were cast for each concrete mix. Specimens were stored in a moist cabinet with temperature of $23^{o}C \pm 2^{o}C$ and relatively humidity of not lower than 95% for 23.5 ± 0.5 hours. The specimens were demoulded at the age of 24 ± 0.5 hours and were measured for the initial reading. The specimens were then cured in a storage room at $23^{o}C \pm 2^{o}C$ and relatively humidity of 50 ± 5% until the age of 365 days. Changes in length of the specimens with respect to their initial reading were measured at the ages of 2, 7, 28, 56, 90, 180 and 365 days and the average of measurement results of three specimens from the same mix is used as to calculate the shrinkage value in microstrain of that concrete mix at that age. Shrinkage measurement results are listed in Table 3 to Table 6 for different mix groups: (1) CSAC/OPC; (2) CSAC/PFA & CSAC/GGBS; (3) CSAC/OPC/PFA & (4)

CSAC/OPC/GGBS for analysis and comparison with pure OPC mix.

In previous study [7], it was found that concrete with different binder combinations of CSAC, OPC, PFA and GGBS would result in different strength development trend due to the inter-alteration of the hydration mechanism among the binders. It was also proved that existence of OPC alters the hydration mechanism of CSAC, PFA and GGBS and thus results in different long-term hydration effect in concrete matrices with different binder combinations [7]. The influences to autogenous shrinkage associated with their different hydration effects, are also reviewed in this study for analyzing the shrinkage development trends of the concrete mixes with different binder combinations. Concrete mixes involved in this study are divided into 4 groups for analysis based on their binder combinations namely blends of CSAC/OPC, CSAC/PFA and CSAC/GGBS, CSAC/OPC/PFA as well as CSAC/OPC/GGBS. Shrinkage values from 1 to 365 days of each concrete mix with different binder combinations are summarized in Table 3 to Table 6 and plotted in Fig. 1 to 4. Compressive cube strengths at ages of 6 hours, 1 day, 7 days, 14 days, 28 days, 90 days, 180 days and 365 days for each concrete mix tested in previous study [7] in accordance with BS EN 12390-3: 2009 "Testing Hardened Concrete [15] are also listed in Table 7 for reference. The cube strength results are used to calculate cylinder strength results, by multiplying the former with the commonly adopted factor or 0.8, to be put in the equation in GL2000 Model for prediction of the ultimate shrinkage strain. Comparison between measured shrinkage values and predicted shrinkage at 365 days using the GL2000 Model with the derived k factors is given in Table 8 and plotted in Figure 5.

Analyses of the results focused on the strength results at 28 days and shrinkage measurement results at 365 days. The former is the key reference value in structural design for concrete structures and is used for putting in the GL2000 Model for predicting ultimate shrinkage performance of the concrete. The latter is used for calculating the ultimate shrinkage strain of the concrete mix for comparison with the value predicted by the GL2000 Model using the derived k factors.

4. DISCUSSION ON TEST RESULT

In cementitious materials like concrete, total shrinkage is mainly composed of autogenous shrinkage and drying shrinkage [17,18]. Autogenous shrinkage is caused by consumption of moisture in the hydration process of cementitious materials while drying shrinkage is the loss of moisture to atmosphere from concrete itself subject to ambient temperature and humidity conditions [17,18]. In this regard, the magnitude and development trend of autogenous shrinkage is dependent on the hydration process of cementitious materials and their combinations, which also determines the strength development trend of concrete. Based on the nature of occurrence of the two shrinkage mechanisms, the ratio of autogenous shrinkage and drying shrinkage depends on the water to binder ratio. The lower the binder ratio, the larger portion of total shrinkage will fall on the part of autogenous shrinkage since there will be less portion of free water in total mixing water for escaping to the atmosphere, other than the portion consumed in hydration. Therefore, the strength development trend of a concrete mix can also be referred to when studying its shrinkage development at least for the part of autogenous shrinkage. In the GL2000 Model employed in this study, shrinkage performance prediction is also based on the 28-day compressive strength of concrete. Since the formula given in the GL2000 Model does not cover concretes with cement types other than types I, II & III classified in ASTM C150-07 [9], the k factor to be put in the formula in this shrinkage prediction model for concretes with binder combinations involved in this study are to be developed in this study with the corresponding measured shrinkage results. Applicability of the GL2000 Model for OPC concrete involved in this study is verified first before using the measured shrinkage results of other concrete mixes to develop corresponding k factors for concretes with other binder combinations. For the verification of the developed k factors, ultimate shrinkage of each concrete mix should be estimated with the measured shrinkage values. Shrinkage development can continue for years with the rate gradually reduced until it finally stops or comes to an equilibrium state with the environment. From Figures 1 to 4, concretes with different binder combinations have their measured shrinkage values falling in relative stable and slow development rates, with little difference from each other, at the age of 365 days. Equations are given in ACI-209.02R-08 [8] and by Neville [23] for relating the development of shrinkage with time. The two equations are basically very similar and that given in equation A1 of ACI-209.02R-08 [8] is used to correlate the shrinkage strain at 365 days with the ultimate shrinkage strain.

$$\varepsilon_t = \varepsilon_{shu} \frac{(t - tc)^{\alpha}}{f + (t - tc)^{\alpha}} \qquad \text{(Equation A1, ACI-209.02R-08)}$$

where $f = 26.0e^{1.42(0.01)(V/S)}$ (Equation A3, ACI-209.02R-08), while V/S is the volume-surface ratio of the test specimen in mm;

For the 75 mm x 75 mm x 285 mm prism test specimens adopted in this study, volume and surface area of test specimens are 1603125 mm^3 and 96750 mm^2 respectively. The V/S is therefore calculated to be 16.57 mm.

Therefore, $f = 26.0e^{1.42(0.01)(V/S)} = 26.0e^{1.42(0.01)(16.57)} = 33$

t_c is equal to 1 day as the specimens start to dry on the next day after casting;

t is an interim age in terms of days for estimating the shrinkage value at that age;

α is equal to 1 as recommended in ACI-209.02R-08;

Therefore, by substituting the value of $f = 33$; $t_c = 1$ and $\alpha = 1$ into Equation A1 of ACI-209.02R-08:

$$\varepsilon_{sh\text{-}365} = 0.92\varepsilon_{shu} \qquad \text{(Equation 1)}$$

Commented [1]: This paragraph is refined to make clear the procedure for coming up with equation 1.

4.1 CSAC/OPC blends

The studied CSAC/OPC mixes are Mix 100/0/0/0, Mix 75/25/0/0, Mix 50/50/0/0, Mix 25/75/0/0, Mix 5/95/0/0 and Mix 0/100/0/0 with their shrinkage measurement results given in Table 3 and plotted in Figure 1. Shrinkage performance of the mix with pure 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 in this study. The pure OPC mix (0/100/0/0) exhibits net shrinkage at the initial stage of the hydration process and continues to develop until 56 days when the shrinkage development slows down with the shrinkage value of 687 microstrain measured at 365 days as shown in Table 3.

Ye'elimite ($C_4A_3\hat{S}$) in CSAC reacts with calcium sulphate in its hydration process to form ettringite crystal ($Ca_6Al_2(SO_4)_3(OH).26H_2O$). It was found in previous studies ettringite crystals induces in the initial hydration process of CSAC coming along with rapid strength gain and early expansion [5, 7,19]. Shrinkage measurement results of the pure CSAC concrete (Mix 100/0/0/0) exhibit its peak expansion at the age of 2 days (+256 microstrain) being the effect of early ettringite formation by CSAC [5,7,9]. Shrinkage actually occurred at the same time but was outperformed by expansion of ettringite crystals resulted with the combined effect of net expansion at this age. This agrees with previous findings observed by Yang et al. [6] and Bizzozero et al. [19] that the expansion of ettringite crystal generated in pure CSAC concrete matrix is most obvious in the first day after casting. Following the cessation of early ettringite formation, measurement results show negative growth of net dimensional change resulted from contest of continuous shrinkage development and decaying expansion. A nearly balanced dimensional change is reached at the age of 28 days (+28 microstrain). Net shrinkage values are recorded at 56 days (-18 microstrain), 90 days (-35 microstrain), 180 days (-148 microstrain) and 365 days (-190 microstrain) but these magnitudes are still considered to indicate good dimensional stability. Results from this study have therefore confirmed that CSAC is able to maintain long-term dimensional stability of concrete. In ACI 209.2R-08 [8], Equation A99 for estimating notable ultimate shrinkage strain ε_{shu} can be expressed as:

$$\varepsilon_{shu} = 900k\left(\frac{30}{fcm_{28}}\right)^{1/2} \text{ microstrain} \qquad \text{(Equation 2)}$$

where the factor k in Equation 2 is the constant for a specified binder type and is denoted as k_x for the respective binder type x. k_{opc} is the shrinkage constant depending on the cement type and for OPC (CEM I) used in this study, k_{opc} = 1 from Table A.14 of the ACI 209.2R-08 Report [8], and fcm_{28} is the concrete mean compressive cylinder strength in MPa. From Table 7, the concrete cube compressive strength at 28 days is 58.7 MPa and taking the commonly adopted correlation factor of 0.8 between cylinder and cube compressive strength, fcm_{28} = 58.7 x 0.8 = 47.0 MPa. By substituting the values of k_{opc} (i.e. 1) and fcm_{28} into Equation 2, the ultimate shrinkage strain (ε_{shu}) is calculated to be 719 microstrain. Based on Equation 1 above, the ultimate shrinkage strain can be calculated by dividing the shrinkage value measured at 365 days with the correction factor of 0.92, i.e. 687 microstrain ÷ 0.92 = 747 microstrain, which agrees well with the calculated value from the GL2000 Model (719 microtrain) with the predicted/calculated shrinkage value ratio of 1.0. In ACI209.2R-08 [8], it mentioned that results from prediction models are not expected to fall within the range of ± 20% of the test data for shrinkage (i.e. range of ratio for test data to the predicted value for ultimate shrinkage strain should be within 0.8 to 1.2). Based on the strong agreement of the ultimate shrinkage value calculated from the measured 365-day shrinkage value and the predicted ultimate shrinkage using the factor k_{opc} of 1.0 given in ACI 290.2R-08 [8], applicability of GL2000 Model is verified in this study.

The measured long-term shrinkage value of pure CSAC concrete (100/0/0/0) at 365-day is 190 microstrains. Based on this measured result, a test figure of 0.29 is put for the k value for CSAC (k_{csac}) in the equation given in GL2000 Model for calculating ε_{shu}. Using Equation 2 above and taking the 28 day cube strength (55.6 MPa) for the pure CSAC concrete (100/0/0/0) from Table 7 with the corresponding cylinder strength of 55.6 MPa x 0.8 = 44.5 MPa, the predicted ultimate shrinkage value is calculated: ε_{shu} = 900 x (0.29) x $\left(\frac{30}{44.5}\right)^{1/2}$ = 214 microstrain, which is again close to the ultimate shrinkage strain obtained by dividing the measured 365-day shrinkage: 190 microstrain ÷ 0.92 = 207 microstrain for the pure CSAC mix and the predicted/calculated shrinkage value ratio tabulated in Table 8 is 1.0. This is again within the acceptable range of ±20% given in ACI209.2R-08 [8]. The assumed k factor for CSAC (k_{csac}) of 0.29 is therefore verified for pure CSAC concrete.

With the replacement of CSAC with OPC in Mixes 75/25/0/0, 50/50/0/0/, 25/75/0/0 and 5/95/0/0, it is obvious that the net shrinkage occurs much earlier (at 7 days) than that of the pure CSAC mix (100/0/0/0). Their shrinkages further develop to different level at 365 days depending on the CSAC content, for which the lower is the CSAC content, the larger is the long-term shrinkage value as shown in Table 3. Whilst, as given in the strength results in Table 7, early strengths at 1 day of the CSAC/OPC blended mixes decreases with reducing CSAC content. Both phenomena can be explained by the reduction in formation of expansive ettringite, which helps increase strength and compensate shrinkage, as discussed in [7]. This is believed to have been resulted from the scrambling of gypsum in CSAC by OPC in the hydration process of CSAC/OPC binder matrix, in which gypsum was consumed in the forestalled reaction with OPC before CSAC [7,20]. The combined effect of reduction in CSAC content in the binder combination and the alteration of its hydration process by OPC is the reduction of early ettringite formation. This also leads to less expansion in concrete to act against shrinkage, thus leading to larger shrinkage magnitude at both early and long-term ages. As a result, the benefits of rapid strength gain and reduced shrinkage properties of concretes using CSAC are both abated when CSAC is replaced by OPC in the binder combination. By citing this observation for the long-term shrinkage performance of concrete with binder combination of CSAC/OPC and comparing with pure CSAC concrete, the shrinkage reducing effect of CSAC seems to have been weakened by the presence of OPC. In CSAC/OPC blended mixes, the combined k factor is dependent on k_{csac} and k_{opc} in proportion to their percentages in the binder combination (i.e. $k_{csac/opc} = k_{csac} \text{ x } \%_{csac} + k_{opc} \text{ x } \%_{opc}$). Using Equation 2 and the assumed value of $k_{csac} = 0.29$ and $k_{opc} = 1.0$ with the percentages of CSAC and OPC in the binder combinations of concrete mixes 75/25/0/0, 50/50/0/0, and 25/75/0/0, the predicted ultimate shrinkage values are calculated to be 351, 474 and 590 microstrains respectively, which are in reasonable agreement with the calculated ultimate shrinkage values by dividing the 365 days results by the conversion factor of 0.92, which are 428, 618 and 773 microstrain with the ratios of predicted/calculated shrinkage value of 0.8, 0.8 and 0.8, which are within the acceptable range of ±20% as given in ACI209.2R-08 [8]. Results of which are listed in Table 8.

4.2 CSAC/PFA and CSAC/GGBS blends

Concrete mixes of CSAC/PFA blends are Mixes 100/0/0/0, 75/0/25/0, 65/0/35/0, 55/0/45/0 and 0/100/0/0 while their shrinkage measurement results are listed in Table 4 with their development trends plotted in Figure 2. Pozzolanic reaction of PFA, which is also termed as secondary hydration, requires the presence of calcium hydroxide inducing in the concrete matrix as the hydration product of OPC [23,24]. Without the presence of OPC in the CSAC/PFA matrix, no calcium hydroxide is generated to reach adequate pH for activating the pozzolanic reaction of PFA, which in turn does not contribute in strength development [7,23]. Lukas et al. [21] observed that pore solutions of CSAC matrix have generally a much lower pH value than that of OPC due to the lack of calcium hydroxide forming in the hydration process of the latter. This phenomenon was confirmed with results of isothermal calorimetry in the same study. As a result, little or none hydration of PFA was able to proceed due to lacking of calcium hydroxide. This agrees with the results obtained in the authors' previous study [7] that there was basically no contribution in strength development by PFA when blended with CSAC only, which does not produce Calcium Hydroxide in its hydration process. When hydration of PFA is not activated without the presence of OPC, no autogenous shrinkage but only drying shrinkage induced by PFA is expected.

In CSAC/PFA blended matrix, it was discovered by Bescher [20] that a "New Self-Organized Structure" of micron-sized (20 – 100 microns) needle-like crystals extending outwards from the vertebrae of PFA would be formed in the hydration process of CSA/PFA blended mix. Nevertheless, the influence of this "New Self-Organized

Structure" on properties of CSAC/PFA concrete including its strength and shrinkage development has not yet been studied.

Shrinkage results obtained in this study for concrete mixes with CSAC/PFA combinations (Mixes 75/0/25/0 and 65/0/35/0) exhibit similar performance trends as those of pure CSAC. This indicates that the "New Self-Organized Structure" in CSAC/PFA blended mixes also does not influence shrinkage development.

The k factor for PFA without the presence of OPC (k_{pfa}) is assumed to be 0.05 for analysis. Taking the combined k factor ($k_{csac/pfa}$) to be the sum of k_{csac} and k_{pfa} with respect to the % proportion of CSAC and PFA in the binder combination, $k_{csac/pfa} = k_{csac} \times \%_{csac} + k_{pfa} \times \%_{pfa}$. By putting the corresponding 28 days cylinder strengths and values for $k_{csac/pfa}$ in mixes 75/0/25/0, 65/0/35/0 and 55/0/45/0 in Equation 2, the predicted ultimate shrinkage values are calculated to be 210, 223 and 206 microstrains respectively, which are in reasonable agreement with the ultimate shrinkage values of 173, 201 and 272 microstrains calculated by dividing the 365-day shrinkage values by the conversion factor of 0.92. The ratio of predicted/calculated shrinkage values are 1.2, 1.1 and 0.8 respectively, which are within the acceptable range of ±20% as given in ACI209.2R-08 [8]. The results are shown in Table 8.

Comparing with CSAC/PFA blended mixes, little study has been done concrete with the binder combination of CSAC/GGBS. Babu et al [24] found that GGBS contributes in strength development, although with little magnitude and in much slower pace, by going through its own hydration process even without the presence of OPC. This self-hydration and slower strength development properties of GGBS are further confirmed in the authors' previous study [7]. In the presence of OPC, both the previous studies of Babu et al [24] and the authors [7] confirmed the contribution of GGBS in strength development by secondary hydration due to its pozzolanic properties, although the strength development pace up to the age of 28 days is still slower than pure OPC concrete with the same binder content and water to binder ratio. Comparing with PFA, GGBS has its own contribution, although little, in the hydration process and thus its influence in shrinkage development, the k factors for GGBS (k_{ggbs}) in concrete without the presence of OPC (i.e. the CSAC/GGBS mixes) is estimated to be 0.07, which is higher than that for PFA. By the same token, 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 % proportion of CSAC and GGBS in the binder combination (i.e. $k_{csac} \times \%_{csac} + k_{ggbs} \times \%_{ggbs}$). Considering the corresponding 28 days cylinder strengths and values for $k_{csac\text{-}pfa}$ in mixes 65/0/0/35 and 35/0/0/65 in Equation 2, the predicted ultimate shrinkage values are 179and 147 microstrains respectively, which are in reasonable agreement with the measured long term shrinkage values of 147 and 184 microstrains with the ratio of predicted/calculated shrinkage value ratios of 1.2 and 0.8, which are both within the acceptable range of ±20% as given in ACI209.2R-08 [8]. Results of which are listed in Table 8.

4.3 OPC/PFA, CSAC/OPC/PFA, & CSAC/OPC/GGBS blends

The concrete mixes studied under this category are 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 and their shrinkage measurement results are given in Table 5 and Table 6 with their shrinkage development trend plotted in Figure 3 and 4. For concrete mixes with OPC/PFA binder combinations (Mixes 0/75/25/0 & 0/65/35/0), shrinkage values at the age of 365 days are slightly lower than that of pure OPC concrete mix (0/100/0/0). Shrinkage reduction performance of PFA as described in some previous studies [16,23] is only obvious at early ages of 28 days to 56 days but drying shrinkage still continues to develop until 365 days. The slow hydration process of PFA with OPC causes slow development of compressive strength but continues to develop evidenced by the results obtained at 365 days. Development of autogenous shrinkage, which is also affected by the hydration process, is therefore slow but does not stop until full completion of hydration process. In this regard, it is considered that PFA only delays the shrinkage development but not reducing shrinkage magnitude in the long run with the presence of OPC. The k factor for OPC/PFA concrete ($k_{opc/pfa}$) in the GL 2000 Model for estimating ultimate shrinkage value of OPC/PFA concrete is the sum of k_{opc} and $k_{pfa\text{-}opc}$ with respect to the % proportion of OPC and PFA (i.e. k_{opc} x $\%_{opc}$ + $k_{pfa\text{-}opc}$ x $\%_{pfa}$). Existence of PFA in OPC/PFA concretes (0/75/25/0 & 0/65/35/0) shows insignificant difference in shrinkage development of pure OPC concrete (0/100/0/0). This agrees with Neville [23], who pointed out that concrete shrinkage is not fundamentally affected by PFA. The $k_{pfa\text{-}opc}$ factor is therefore estimated to be 1.0. By substituting these k values, percentages of each binder and the corresponding cylinder strength of each OPC/PFA mix to Equation 2, the predicted ultimate shrinkage values for mixes 0/75/25/0 and 0/65/35/0 are 793 & 826 microstrains respectively. These predicted results are in reasonable agreement with the calculated ultimate shrinkage values of 784 & 743 microstrains with the ratio of predicted/calculated shrinkage values of 1.0 and 1.1 respectively as shown in Table 8.

It has been confirmed in previous study [7] that calcium hydroxide given out in the hydration process of small amount of OPC (5%) is already sufficient to activate the pozzolanic reaction of PFA and GGBS. Their contributions in hydration, although in very slow pace, are able to make the concretes achieve similar long-term strength as pure OPC mix at the age of 365 days. At the same time, as mentioned previously, there is no influence of CSAC on PFA in the binder combination since there is no hydration effect between them. For CSAC/OPC/PFA mixes, the factors k_{csac}, k_{opc} and $k_{pfa\text{-}opc}$ are taken as 0.29, 1.0 and 1.0 as previous derived. By substituting these k factors, percentages of each binder and the corresponding cylinder strength of each CSAC/OPC/PFA mix to Equation 2, the predicted ultimate shrinkage values for 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 575, 640, 699, 451 and 476 microstrains respectively. These predicted results are in reasonable agreement with the ultimate shrinkage values of 715, 695, 790, 367 and 398 microstrains with the ratios of predicted/calculated shrinkage values of 0.8, 0.9 and 0.9, 1.2 and 1.2 respectively, which are within the acceptable range of ±20% as given in ACI209.2R-08 [8]. Results of which are listed in Table 8.

As indicated by Neville [23], incorporation of GGBS in concrete induces larger initial shrinkage but does not incur significant change in the long-term shrinkage. This previous finding agrees with the measured long-term shrinkage results of CSAC/OPC/GGBS mixes (32.5/32.5/0/35 & 17.5/17.5/0/65) in this study when comparing with the result of the pure OPC mix (0/100/0/0). The measured shrinkage values of CSAC/OPC/GGBS mixes (32.5/32.5/0/35 & 17.5/17.5/0/65) before the age of 90 days in this study are lower than those of the pure OPC mix (0/100/0/0), which is not in line with the Neville's [23] findings. This is believed to be the effect of the existence of CSAC in the binder content, which exhibits early expansion due to ettringite formation. When examining the measured shrinkage values at the age of 365 days, these two CSAC/OPC/GGBS mixes are similar to that of the pure OPC mix. The estimated k value for GGBS with the existence of OPC ($k_{ggbs\text{-}opc}$) is therefore taken as 1.0 while those for CSAC and OPC (k_{csac} and k_{opc}) are remained as 0.29 and 1.0., By substituting these k factors, percentages of each binder and the corresponding cylinder strength of each CSAC/OPC/GGBS mix into Equation 2, the predicted ultimate shrinkage values for the Mixes 32.5/32.5/0/35 and 17.5/17.5/0/65 are 593 and 766 microstrains respectively, which are well agreed by the calculated ultimate shrinkage values of 662 and 701 microstrains with the ratios of predicted/calculated shrinkage values of 0.9 and 1.1 respectively, which are within the acceptable range of ±20% as given in ACI209.2R-08 [8].

All the predicted ultimate shrinkage values based on the derived k factors for different binders (CSAC, OPC, PFA and GGBS) using Equation 2 modified from the GL2000 Model are compared with the ultimate shrinkage values calculated with Equation 1 by dividing the measured 365-day shrinkage values with the conversion factor of 0.92. The two sets of results are plotted in Figure 5

4.4 Verification of the applicability of ACI-209.02-08 for the derived model by calculating shrinkage values at other ages based on the predicted ultimate shrinkage

Commented [2]: New sub-section added

The predicted ultimate shrinkage values are calculated using the GL2000 Model with the derived k factors for each binder materials. The ultimate shrinkage value of each concrete mix represents the predicted ultimate change with respect to the initial hardened dimension. Concrete mixes incorporating CSAC perform differently that the formation of ettringite crystals at early ages induces expansion right after hardening but stops shortly afterwards in the order of one to several days [1], which is then gradually compensated by shrinkage. When a reverse direction of dimensional change (from expansion to shrinkage) is observed from the readings, the previous measured shrinkage value can be taken as the starting point for net shrinkage and its measured shrinkage value as shrinkage datum for correction (ε_{shd}). Subsequently, the corrected shrinkage values (CSV) at each age can be calculated by subtracting the reading taken at the starting point by the measured shrinkage value at that age. Based on Equation 1 above, the CSV at 365 days can be used to calculate the corrected ultimate shrinkage value with respect to the zero point, where expansion ends and shrinkage starts.

$\varepsilon_{sh-365} = 0.92\varepsilon_{shu}$ (Equation 1) can be revised to:

$\varepsilon_{csh-365} = 0.92\varepsilon_{cshu}$ (Equation 3)

where $\varepsilon_{csh-365}$ is the corrected shrinkage value at 365 days, and

ε_{cshu} is the corrected ultimate shrinkage value

Take the example of concrete mix 100/0/0/0,

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

By substituting it into Equation 3,

$\varepsilon_{cshu} = \varepsilon_{csh-365} \div 0.92 = -446 \div 0.92 = -485$ microstrain

Equation A-1 given in ACI-209.02R-08 applies to concrete made of Type I and III cement for estimating shrinkage strain at interim ages with respect to its ultimate shrinkage strain.

$\varepsilon_t = \varepsilon_{shu} \frac{(t - tc)^{\alpha}}{f + (t - tc)^{\alpha}}$ (Equation A1, ACI-209.02R-08)

By substituting the values of $f = 33$, $t_c = 1$ *and* $\alpha = 1$ into Equation A-1 of ACI-209.02R-08 and using the corrected ultimate shrinkage value (ε_{cshu}) instead of the ultimate shrinkage value, the equation becomes:

$$\varepsilon_{tc} = \varepsilon_{cshu} \frac{(t-1)^1}{33+(t-1)^1} \qquad \text{(Equation 4)}$$

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

Since $\varepsilon_{tc} = \varepsilon_t - \varepsilon_{shd}$; $\varepsilon_t = \varepsilon_{tc} + \varepsilon_{shd}$

Taking an example of concrete mix 100/0/0/0 again, shrinkage value at 28 days can be calculated as follow.

$$\varepsilon_{28} = \varepsilon_{cshu} \frac{(28-1)^1}{33+(28-1)^1} + \varepsilon_{shd} = -485 \text{ x } \frac{(28-1)^1}{33+(28-1)^1} + 256 = 28 \text{ microstrain}$$

Similarly, estimated shrinkage values at all ages for all concrete mixes are calculated and tabulated in Table 9 for comparing with the measured shrinkage values. The calculated shrinkage values are plotted against the measured shrinkage values in Figures 6 to 25. The coefficients of determination in the figures give indication of good correlation between the two sets of data. This verifies that the equations A-1 and A-99 given in ACI-209.2R-08 are also applicable for predicting ultimate shrinkage values and interim shrinkage values for concretes with various binder combinations of CSAC, OPC, PFA and GGBS providing the k factors to be put in equation A-99 are accurately derived.

4.5 Summary and Conclusion

The findings of the study verified that the long-term shrinkage of concrete is dependent on the 28-day compressive strength and the binder combination, based on which the GL2000 Model was established. While the GL2000 Model only provides predictions, based on k factors, for Portland Cement (Type I, II & III classified in ASTM C150-07 "Standard Specification for Portland Cement" are given, this study succeeds to fill up the gap by deriving different k factors for other commonly used binder combinations in concrete as summarized in the following for the adoption in the same model to predict ultimate shrinkage.

Prediction Model for Ultimate Shrinkage:

$$\varepsilon_{shu} = 900k_{bc}\left(\frac{30}{fcm_{28}}\right)^{1/2} \text{ microstrain}$$

Where k_{bc} is the combined k factor of binder combination calculated by $\Sigma(k_b \text{ x } \%_b)$ with individual k factor for each binder material given below.

k_{csac} = 0.29 (CSAC)
k_{opc} = 1.0 (OPC)
k_{pfa} = 0.05 (PFA without the presence of OPC)
$k_{pfa\text{-}opc}$ = 1.0 (PFA with presence of OPC)
k_{ggbs} = 0.07 (GGBS without the presence of OPC)
$k_{ggbs\text{-}opc}$ = 1.0 (GGBS with presence of OPC)

The above k factors are used to predict the ultimate shrinkage values (ε_{shu}) of concrete mixes with different binder combinations using equation (1) above based on the GL2000 Model in ACI 209.2R-08: "Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete" [8].

Predicted ultimate shrinkage values = $\varepsilon_{shu} = 900k\left(\frac{30}{fcm_{28}}\right)^{1/2}$ with the unit of microstrain; in which the factor k 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 % in the concrete mix,

i.e. combined k factor = $\Sigma(k_b \times \%_b)$, where b is the binder material involved in the total binder content, k_b is the individual k factor for the binder material b as listed above and $\%_b$ is the percentage of binder material b in the total binder content. The combined k factors for different binder combinations used in the concrete mixes in this study are calculated and listed in Table 8.
The combined k factors for different combinations used in the concrete mixes in this study are calculated and listed in Table 8. Comparison of the predicted ultimate shrinkage and the measured long-term shrinkage values are also listed in Table 8 and plotted in Figure 5. The correlation of determination of 0.9 in the relationship curve shows good estimation of the predicted ultimate shrinkage values comparing to the ultimate shrinkage values calculated from measured values at 365 days. In addition, all the ratios between individual predicted ultimate shrinkage value and the calculated ultimate shrinkage value are in the range of 0.8 to 1.2, which are within the acceptable range of ±20% as given in ACI209.2R-08 [8].

Equation 4 was derived for validating the predicted ultimate shrinkage values and measured shrinkage values at interim ages from 2 days to 365 days. For concretes incorporating CSAC, expansion exhibits at the initial stage and is gradually compensated by shrinkage. The measured reading at the concrete age showing maximum expansion is taken as the zero point for commencement of shrinkage. The measured 365-day shrinkage value was then used to calculate the corrected 365-day shrinkage value by subtracting the reading at the zero point. The result was then used to calculate the predicted corrected ultimate shrinkage value. Calculated shrinkage values at different ages were obtained for the comparison with the measured shrinkage values at corresponding ages. Good correlations of the two sets of calculated and measured shrinkage values are obtained. The two equations, A-1 and A-99, given in the above ACI report for concretes using cement types I, II & III are both verified to be also applicable to concretes with binder combinations included in this study with the newly derived k factors for the binder materials of CSAC, OPC, PFA and GGBS.

Based on the above, the prediction model and the k factors developed in this study is considered to be accurate enough for predicting the ultimate shrinkage value of a concrete mix using combinations of binder materials involved in this study. Such prediction will be useful at the design stage for structural designers for considering the risk of crack formation, loss of prestress and other potential defects relating to ultimate dimensional change due to shrinkage development.

Since this study only examined the shrinkage performance of different binder combinations of CSAC, OPC, PFA and GGBS with one water to binder ratio of 0.45, concretes with other water to binder ratios may give different magnitudes of shrinkage performance although the influence of different binder combinations should be similar. As mentioned earlier in this paper, shrinkage development is composed of autogenous shrinkage and drying shrinkage while only the former is dependent on the hydration of different binder combinations. As such, shrinkage development trend of concrete with higher water to binder may be more dependent on drying shrinkage, which is solely the loss of moisture from concrete matrix to the atmosphere. As a result, the equations developed for predicting the shrinkage performance of different binder combinations may only be applicable to concrete with water to binder ratio of 0.45 or below, which is deemed good enough to cover most concrete mixes requiring early strength by using CSAC or its combination with other binder materials including OPC, PFA and GGBS.

Nevertheless, studies on the influence of variation in water to binder ratio of concrete mixes with different binder combinations of CSAC, OPC, PFA and GGBS are recommended.

In general, although the k factors for different binder materials to be used in the GL2000 Model are dependent on the interactions of binders in different combinations of CSAC, PFA or GGBS blended with OPC, the most commonly used % contents of these binder materials have already covered in this study.

5. Acknowledgement

This study is part of the intensive research on different properties of concrete using CSAC blended with OPC and PFA or GGBS in different binder combinations. A total of 20 concrete mixes were involved and numerous test specimens for different properties were prepared and tested by technicians of Multi-Way Industries Ltd. at the rest time on weekends. Special thanks are also given to the suppliers of materials used in this study including CTS Cement Corporation, China Light & Power Co., Ltd., K-Wah Building Materials Co., Ltd, and BASF (HK) Ltd. for their sponsorship of CSAC, PFA, GGBS and concrete admixtures respectively. The authors would like to dedicate this paper to the material suppliers, technicians and all other parties who have contributed their selfless contribution to the completion of this research work.

Tables and Figures:

Table 1: Materials used in the study

Material	**Main Ingredients**					
CSAC	Clinker: 82%				Addition: 18%	
	Yeelimite		Belite	Others		Anhydrous Calcium Sulfate
	58%		12%	12%		18%
Other Binders	CaO	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

Table 2: Mix designs used in the study

Mix Identification	**Binders (in kg/cum of concrete)**				Admixture (in liter/cum of concrete)	
	CSAC	**OPC**	**PFA**	**GGBS**	**SP8S**	**Develcrete**
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 1:

(a) SP8S (manufacturer: BASF) is used to attain the concrete workability to be within the acceptable tolerable for designed slump of 175 mm.

(b) Delvocrete Stabilizer (manufacturer: BASF) is used to regulate the workable time of concrete mixes having CSAC to at least 1 hour for placing

(c)

Table 3: Shrinkage Results of Mix Group 1 at Different Ages

Mix Identification	2~~1~~ day	7 days	28 days	56 days	90 days	180 days	365 days
	Shrinkage in microstrain (+ve: expansion; -ve: 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 4: Shrinkage Results of Mix Group 2 at Different Ages

Mix Identification	2~~1~~ day	7 days	28 days	56 days	90 days	180 days	365 days
	Shrinkage in microstrain (+ve: expansion; -ve: 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: Shrinkage Results of Mix Group 3 at Different Ages

Mix Identification	2~~1~~ day	7 days	28 days	56 days	90 days	180 days	365 days
	Shrinkage in microstrain (+ve: expansion; -ve: 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

Commented [3]: In tables 3 to 6, the age at which the first shrinkage measurement made is corrected to be 2 days. According to ASTM C157/C157M – 08 (2014), the initial reading is taken at the demoulding time of 24 hours after casting, the first shrinkage measurement reading is taken 1 day afterward, which is 2 days of concrete age. The authors felt sorry for this minor mistake.

Table 6: Shrinkage Results of Mix Group 4 at Different Ages

Mix Identification	21 day	7 days	28 days	56 days	90 days	180 days	365 days
	Shrinkage in microstrain (+ve: expansion; -ve: 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 7: Compressive Strength Results (cube strength) of all Mixes at Different Ages

Mix Identification	6 hrs	1 day	7 days	14 days	28 days	90 days	180 days	365 days
	Compressive Strength in MPa							
100/0/0/0	34.7	40.1	46.3	53.5	55.6	57.8	65.4	65.8
75/25/0/0	21.5	27.3	36.2	40.7	54.5	55.0	58.4	58.9
50/50/0/0	12.6	16.4	37.4	45.7	57.0	62.1	62.1	62.1
25/75/0/0	8.0	9.4	44.8	48.5	58.6	68.6	68.6	68.6
75/0/25/0	22.8	25.6	33.5	33.6	36.5	37.1	39.0	41.7
65/0/35/0	20.7	22.8	24.6	26.3	27.0	28.8	29.4	32.3
55/0/45/0	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	7.2	8.8	24.2	37.0	48.9	61.2	65.1	67.1
32.5/32.5/35/0	5.2	6.0	18.6	31.2	44.0	62.1	63.9	64.1
27.5/27.5/45/0	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	12.7	15.5	16.3	16.9	37.4	46.2	50.5	64.4
65/10/25/0	11.4	14.5	15.8	15.8	39.1	50.4	61.3	65.5
65/0/0/35	16.3	23.2	31.6	31.6	41.8	48.9	56.7	59.3
35/0/0/65	4.9	6.9	12.7	21.0	31.7	41.6	49.3	57.2
32.5/32.5/0/35	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 there was not enough strength of the concrete for demoulding

Table 8: Comparison between Predicted Ultimate Shrinkage (GL2000 Model) and Measured Long term Shrinkage

Mix ID	**28-D cube strength (MPa)**	**28-D cylinder strength (MPa)**	**$\%_{csac}$**	**k_{csac}**	**$\%_{opc}$**	**k_{opc}**	**$\%_{pfa}$**	**k_{pfa} or $k_{pfa\text{-}opc}$**	**$\%_{ggbs}$**	**k_{ggbs} or $k_{ggbs\text{-}opc}$**	**Ultimate shrinkage**				
											Combined k	Predicted by GL2000 Model	Measured 365-day shrinkage	Calculated ultimate shrinkage	Ratio of Predicted/ Calculated Ultimate shrinkage
												Microstrain			
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 9: Shrinkage Results of Mix Group 1 at Different Ages

Commented [4]: New table added

Mix ID	**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 value calculated from C-USV with equation A-1 in ACI-209.2R-08.

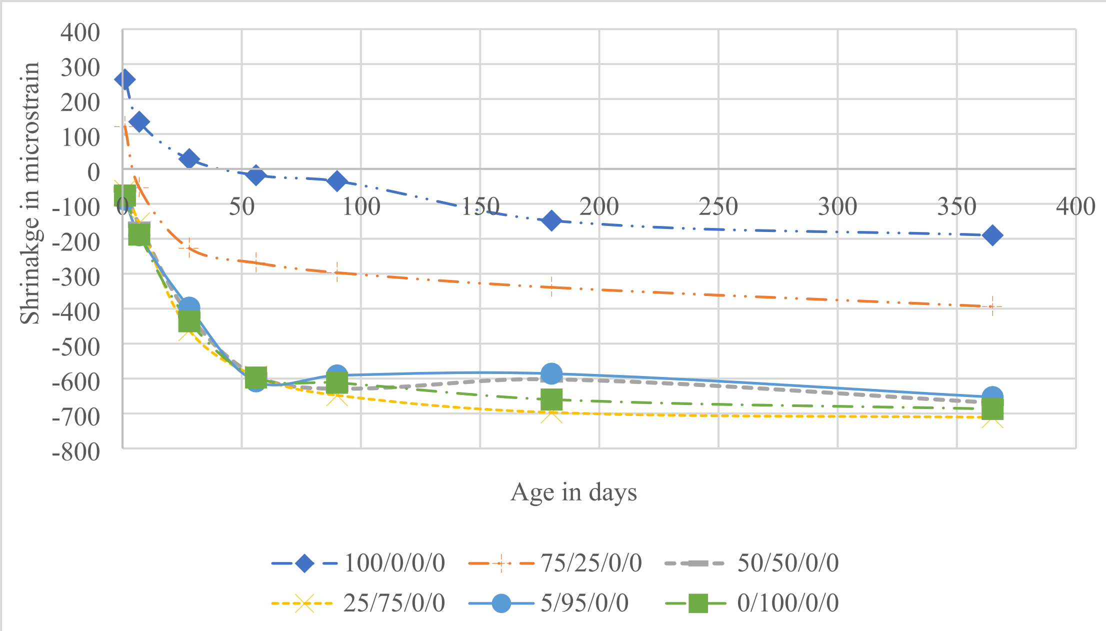

Figure 1: Shrinkage development trends of CSAC, OPC & CSAC/OPC Mixes

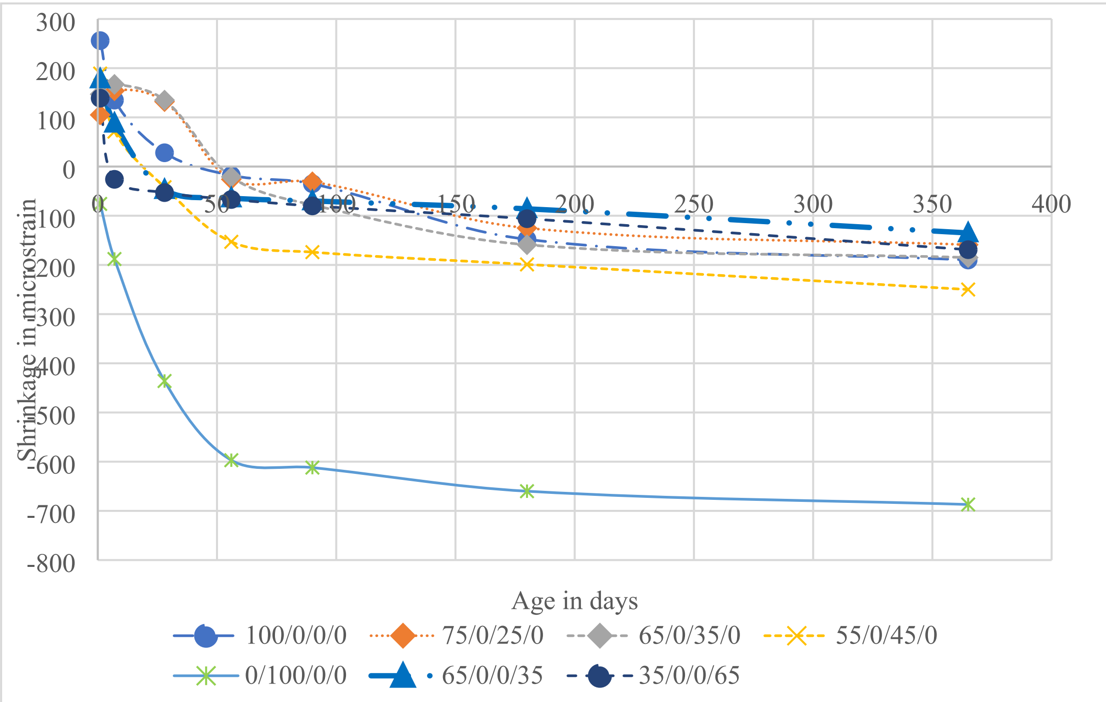

Figure 2: Shrinkage development trends of CSAC, OPC, CSAC/PFA & CSAC/GGBS Mixes

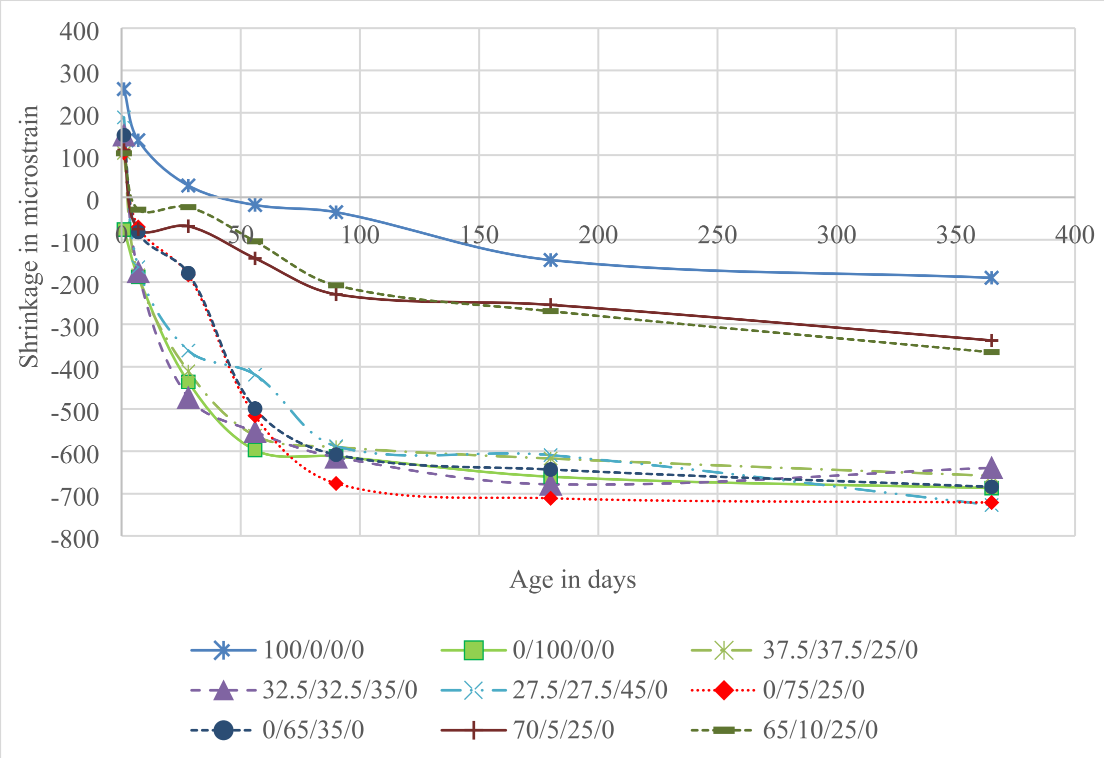

Figure 3: Shrinkage development trends of CSAC, OPC & CSAC/OPC/PFA Mixes

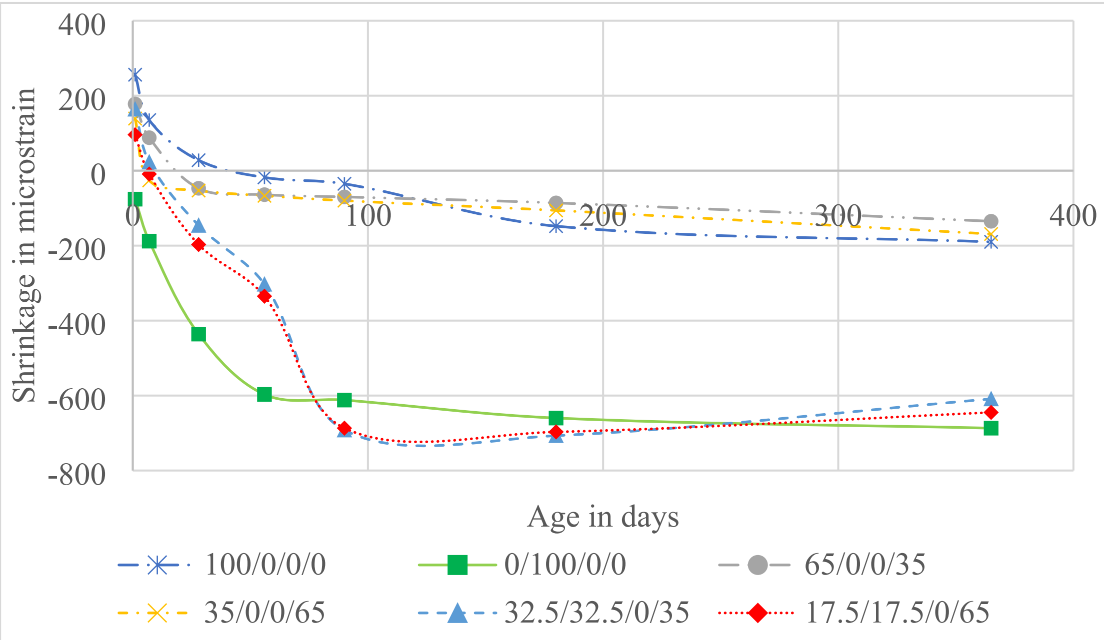

Figure 4: Shrinkage development trends of CSAC, OPC & CSAC/OPC/GGBS Mixes

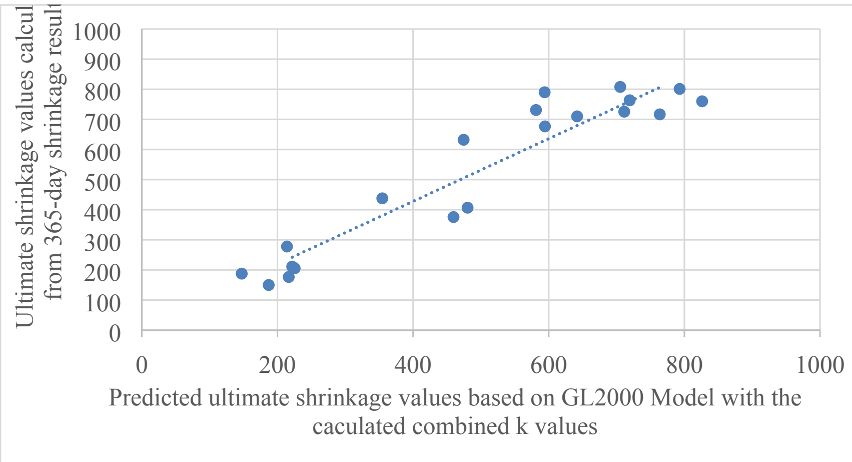

Figure 5: Correlation between Predicted/Calculated Ultimate Shrinkage Values Based on GL2000 Model

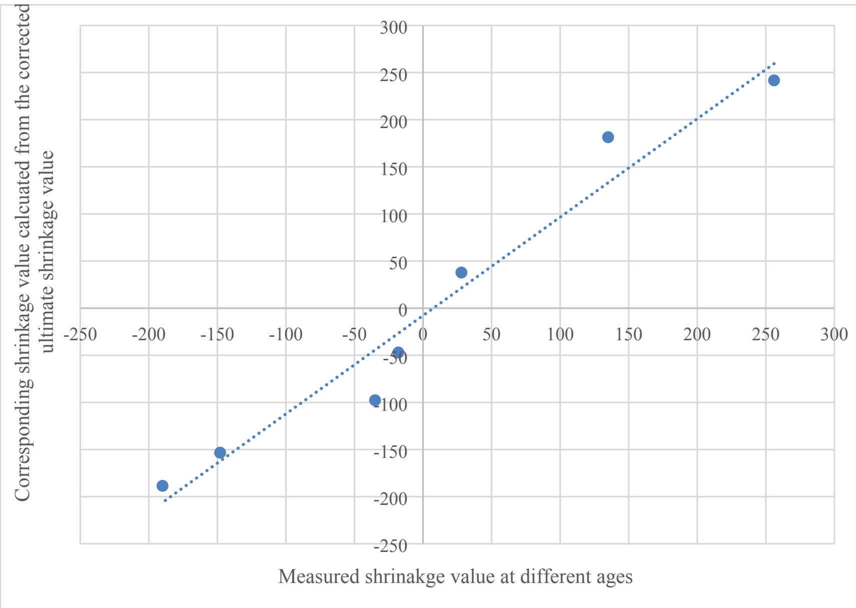

Figure 6: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 100/0/0/0

Commented [5]: Figures 6 – 25 newly added

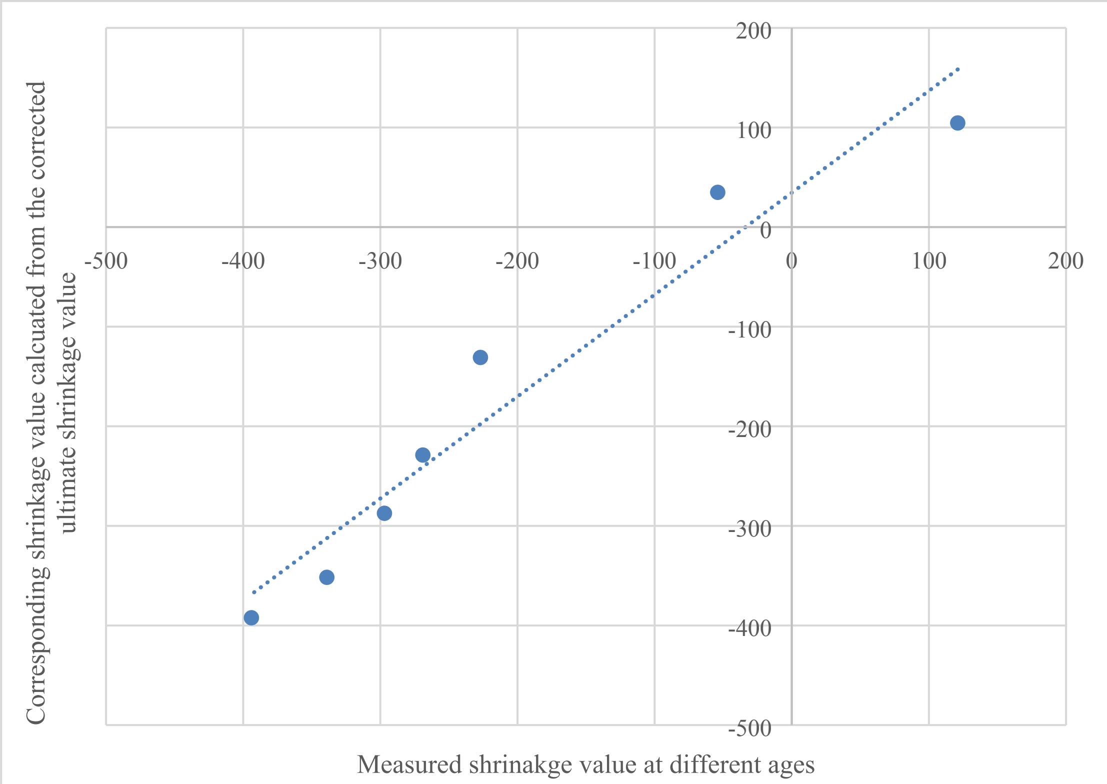

Figure 7: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 75/25/0/0

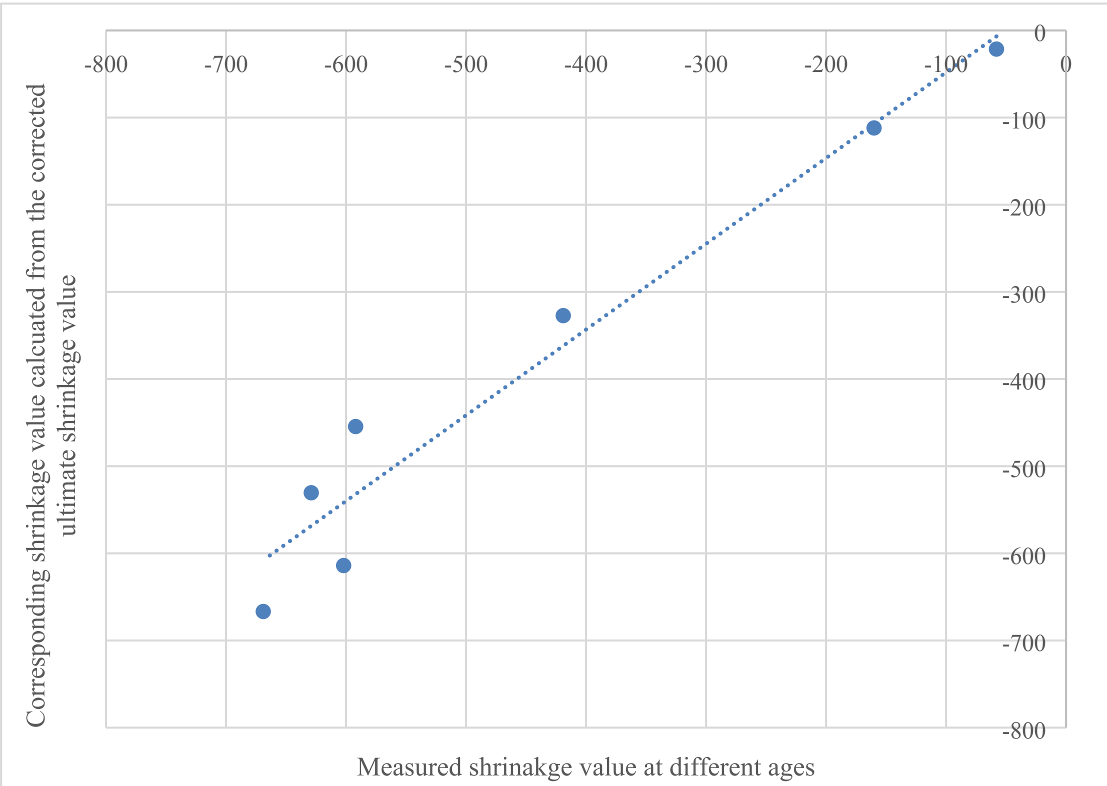

Figure 8: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 75/25/0/0

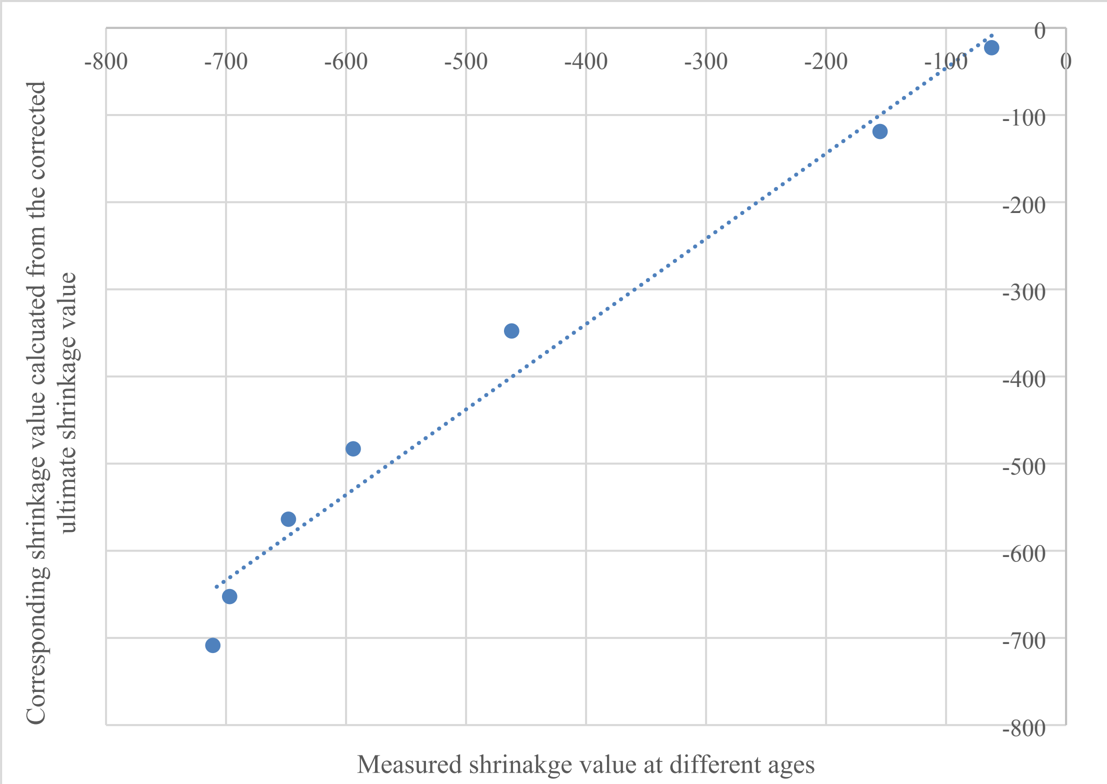

Figure 9: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 25/75/0/0

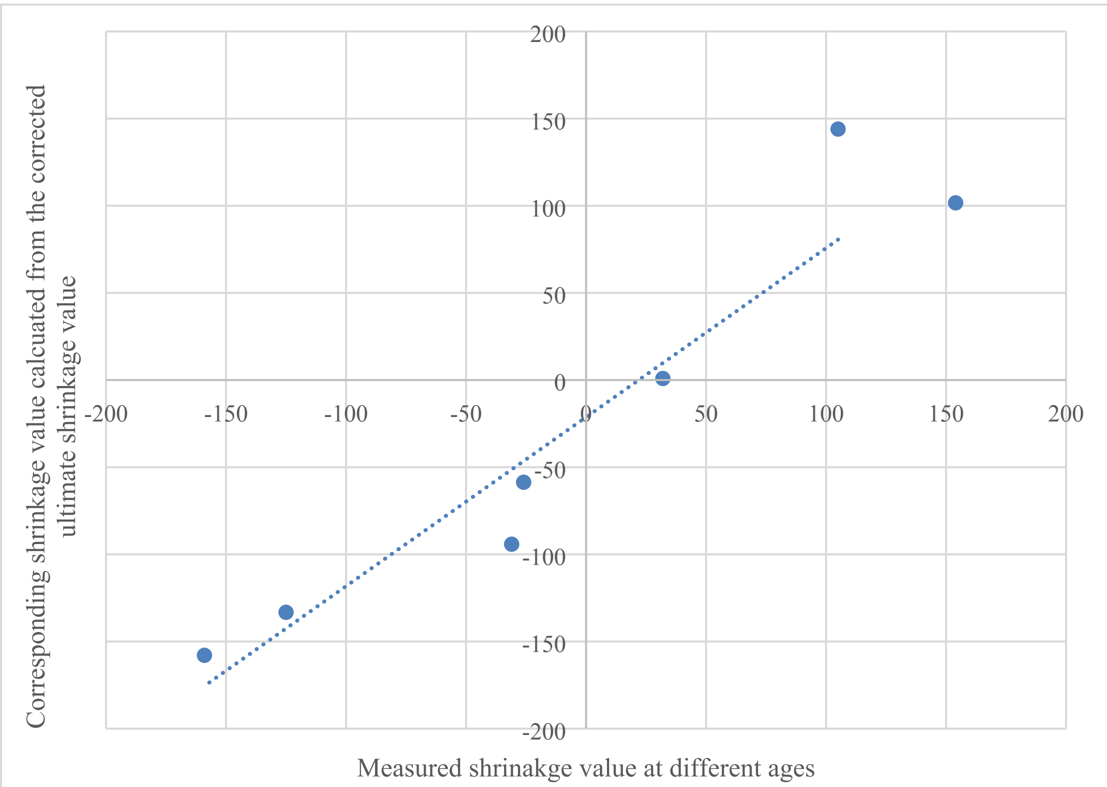

Figure 10: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 75/0/25/0

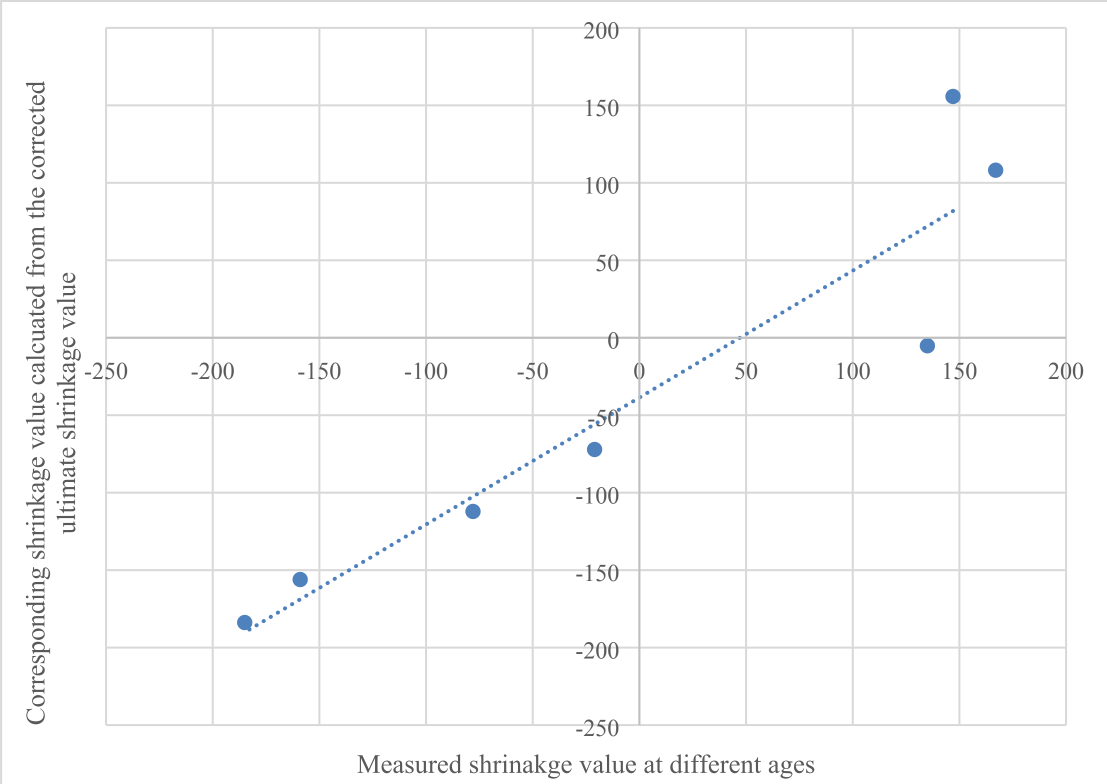

Figure 11: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 65/0/35/0

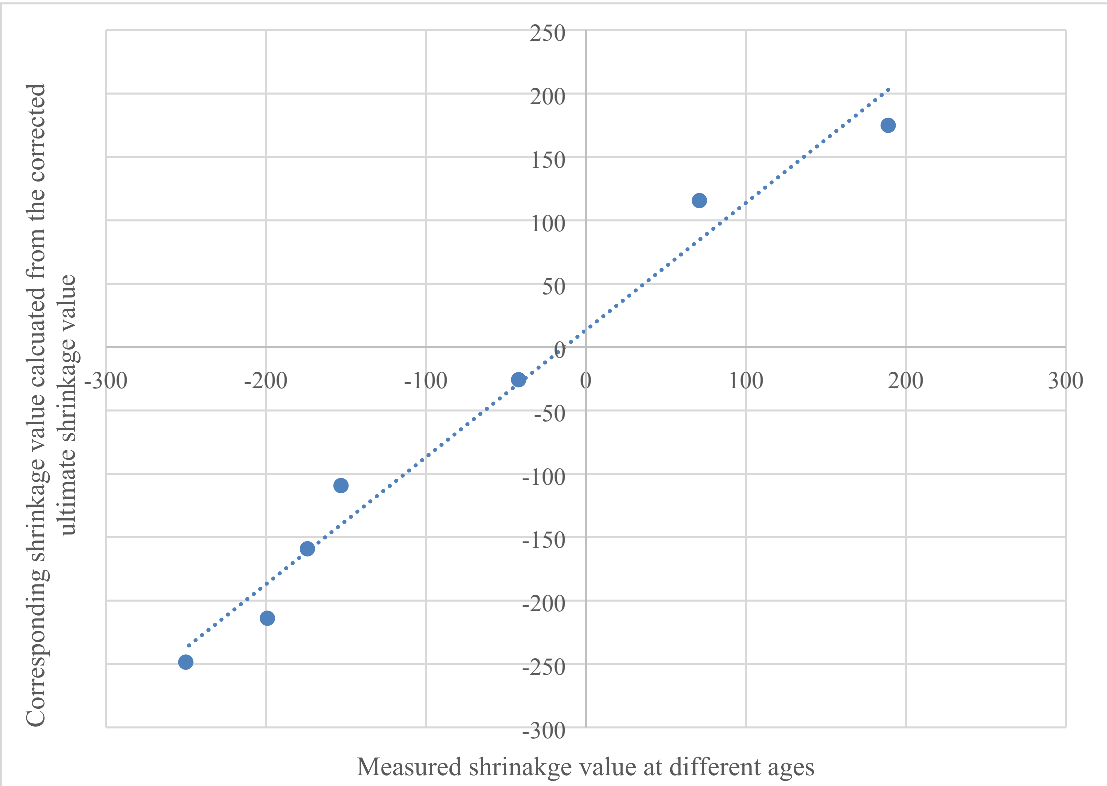

Figure 12: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 55/0/45/0

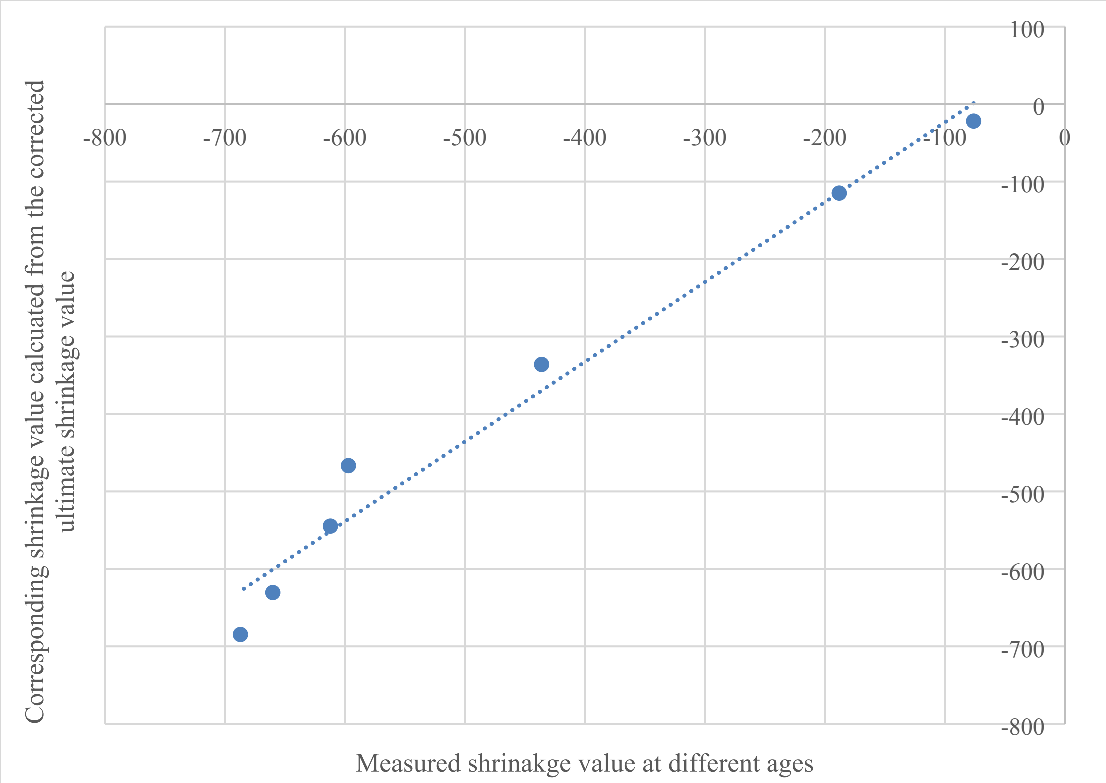

Figure 13: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 0/100/0/0

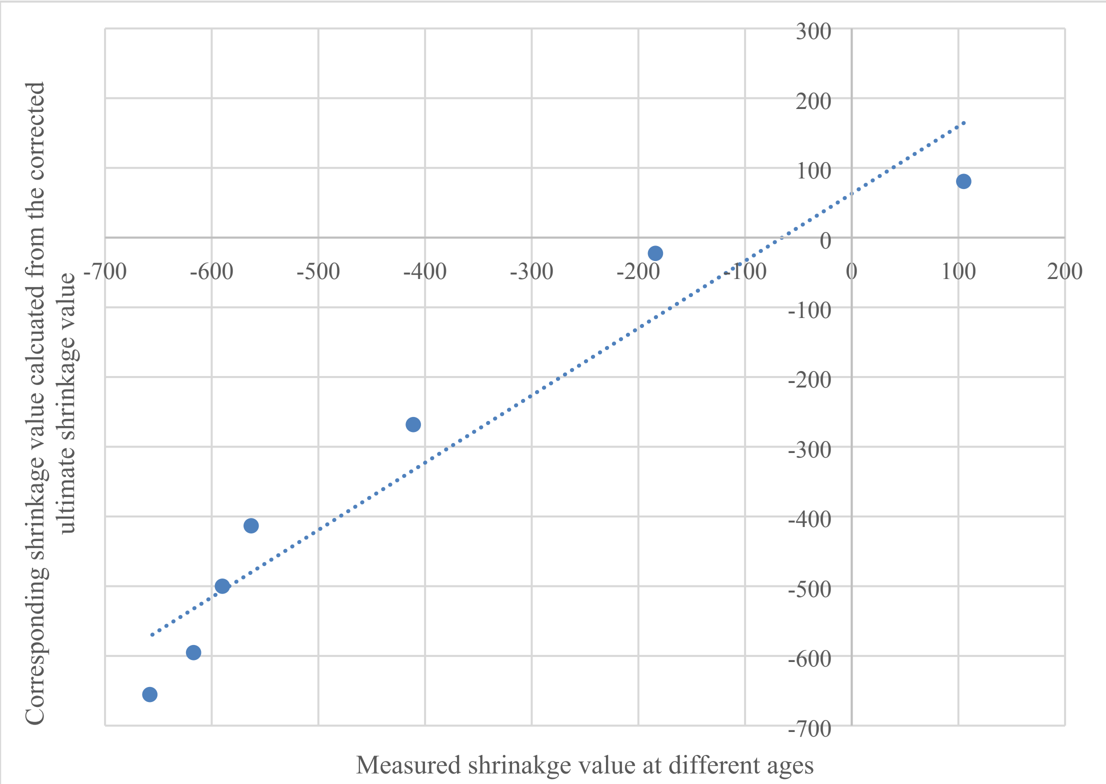

Figure 14: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 37.5/37.5/25/0

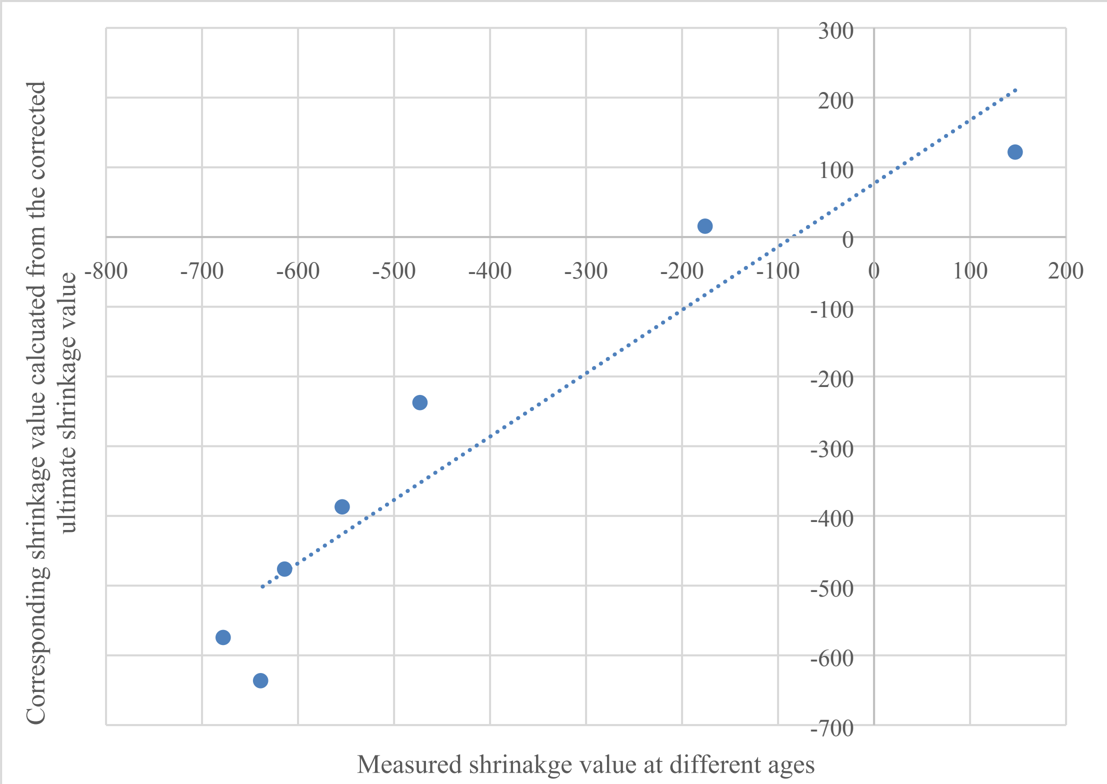

Figure 15: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 32.5/32.5/35/0

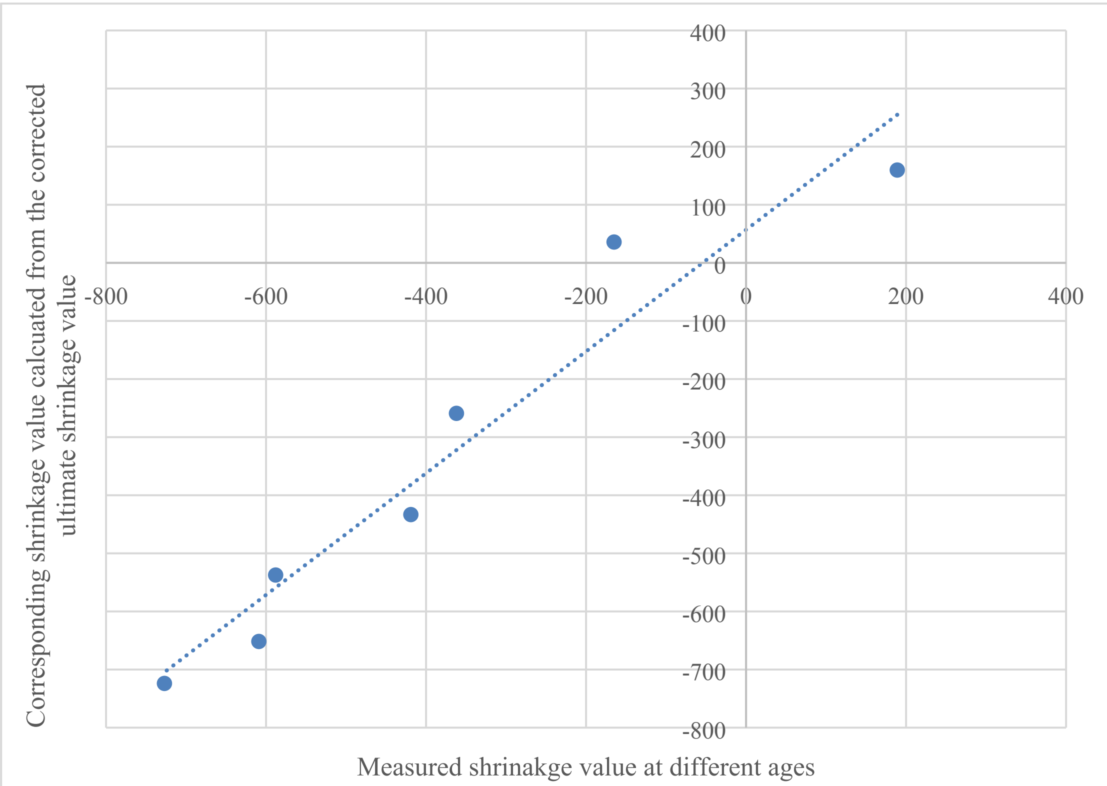

Figure 16: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 27.5/27.5/45/0

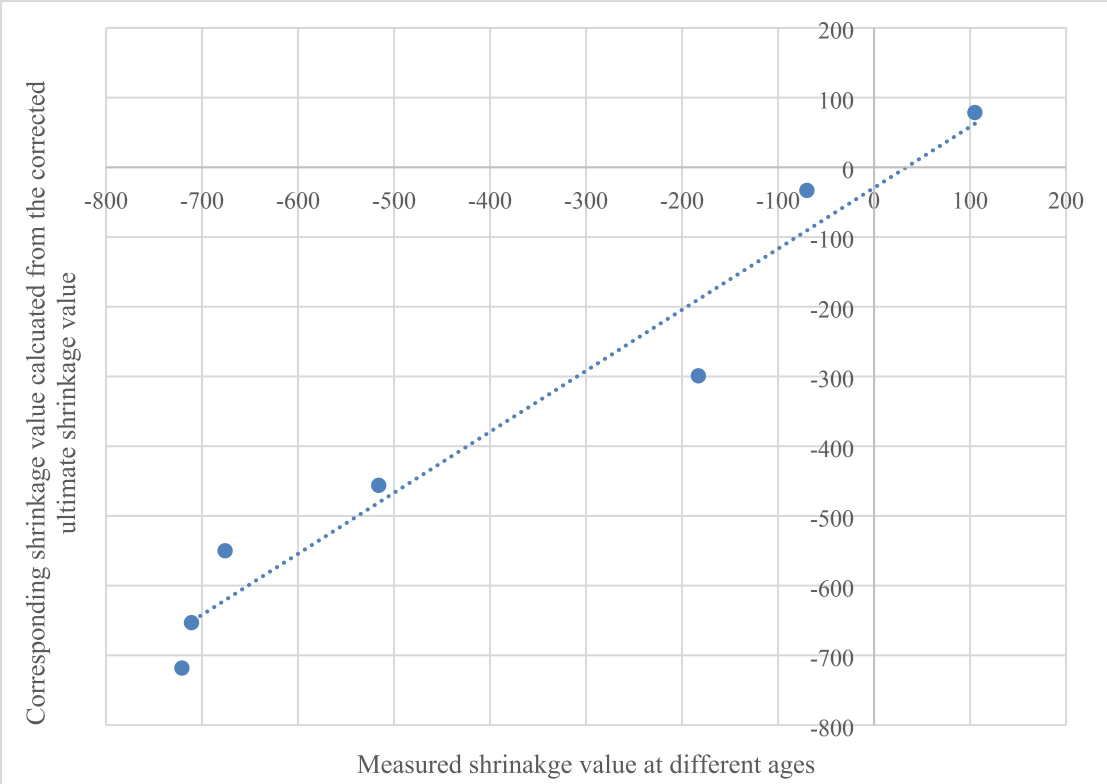

Figure 17: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 0/75/25/0

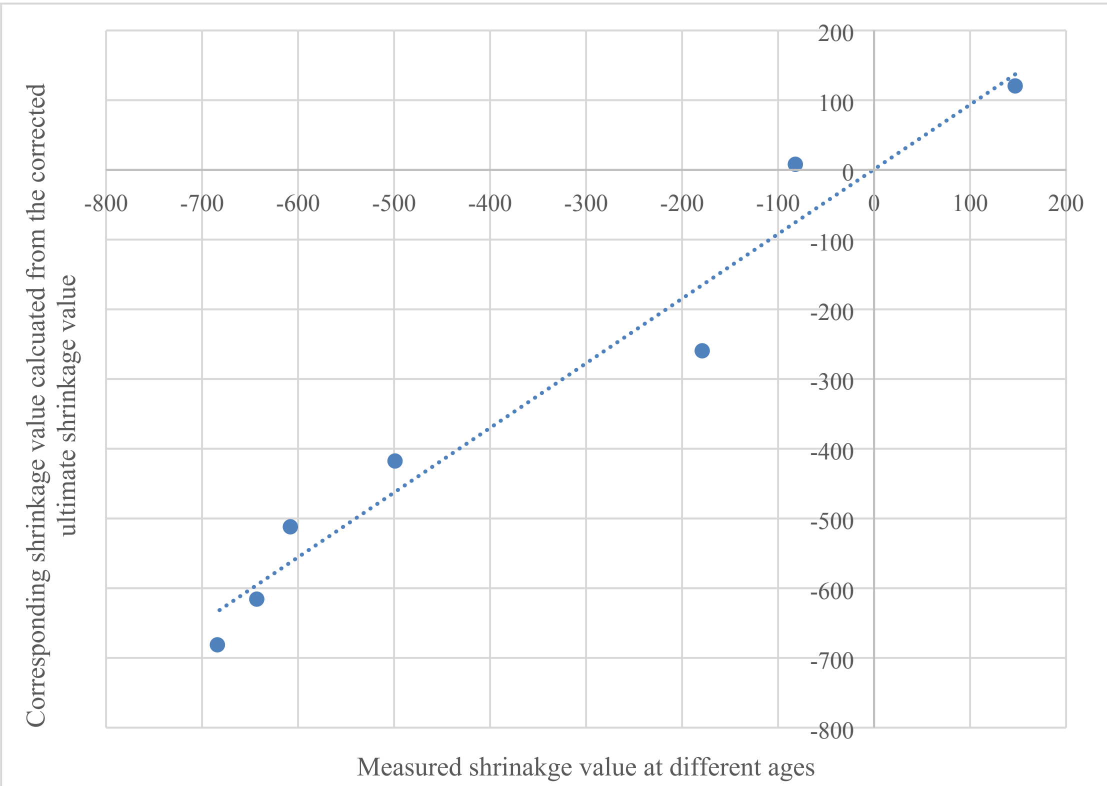

Figure 18: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 0/65/35/0

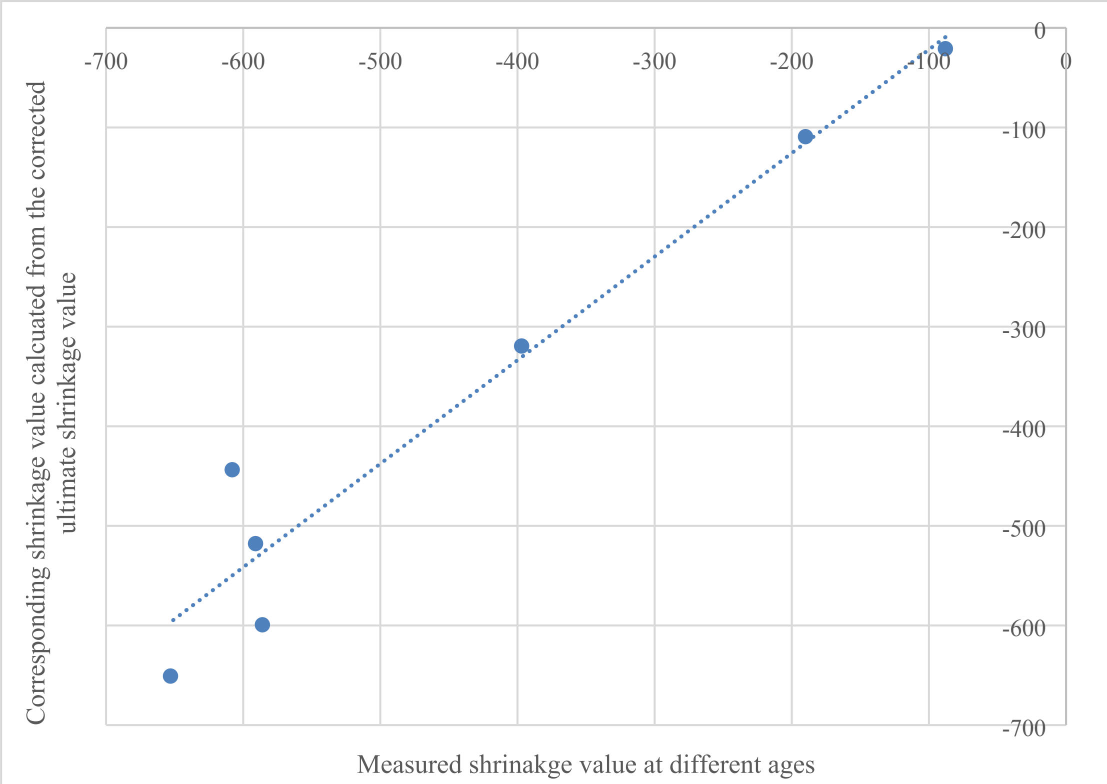

Figure 19: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 5/95/0/0

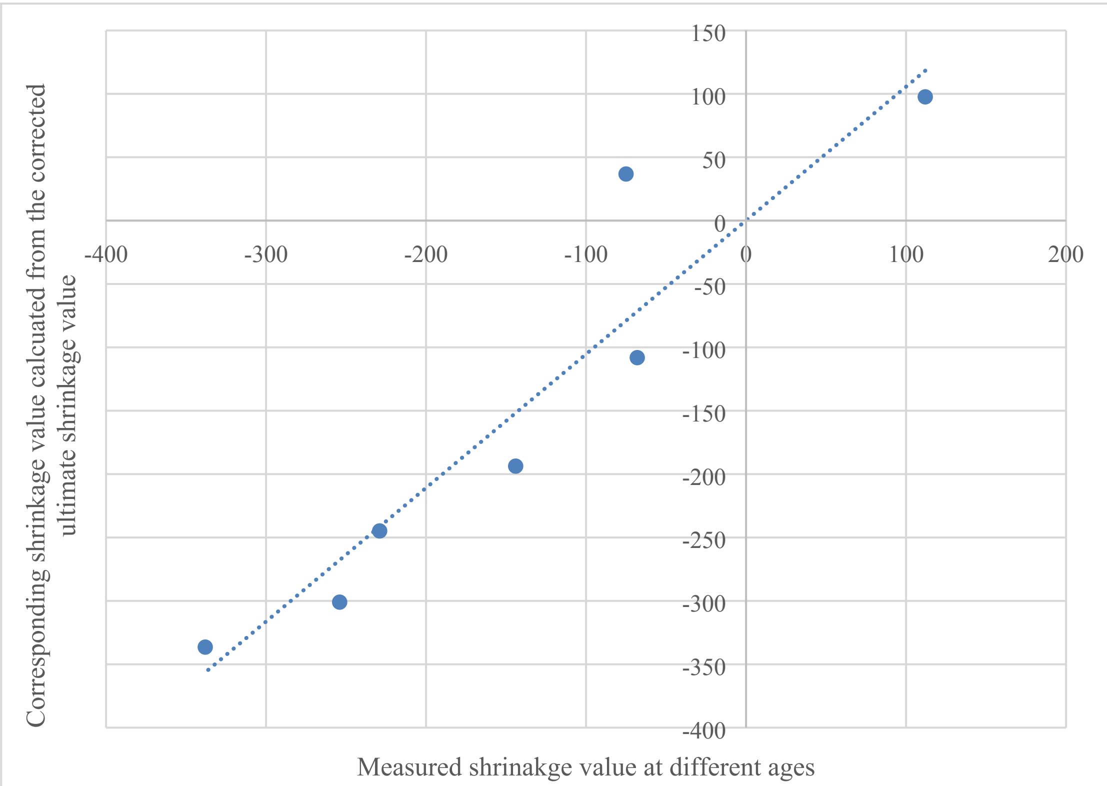

Figure 20: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 70/5/25/0

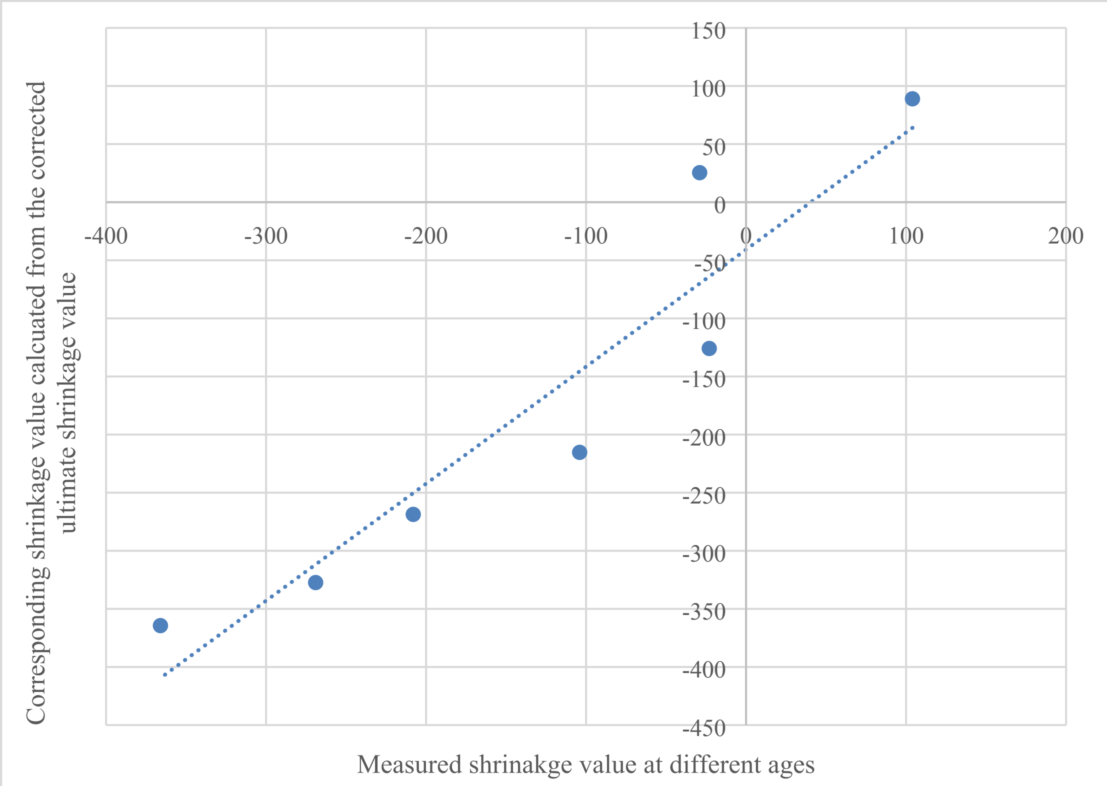

Figure 21: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 65/10/25/0

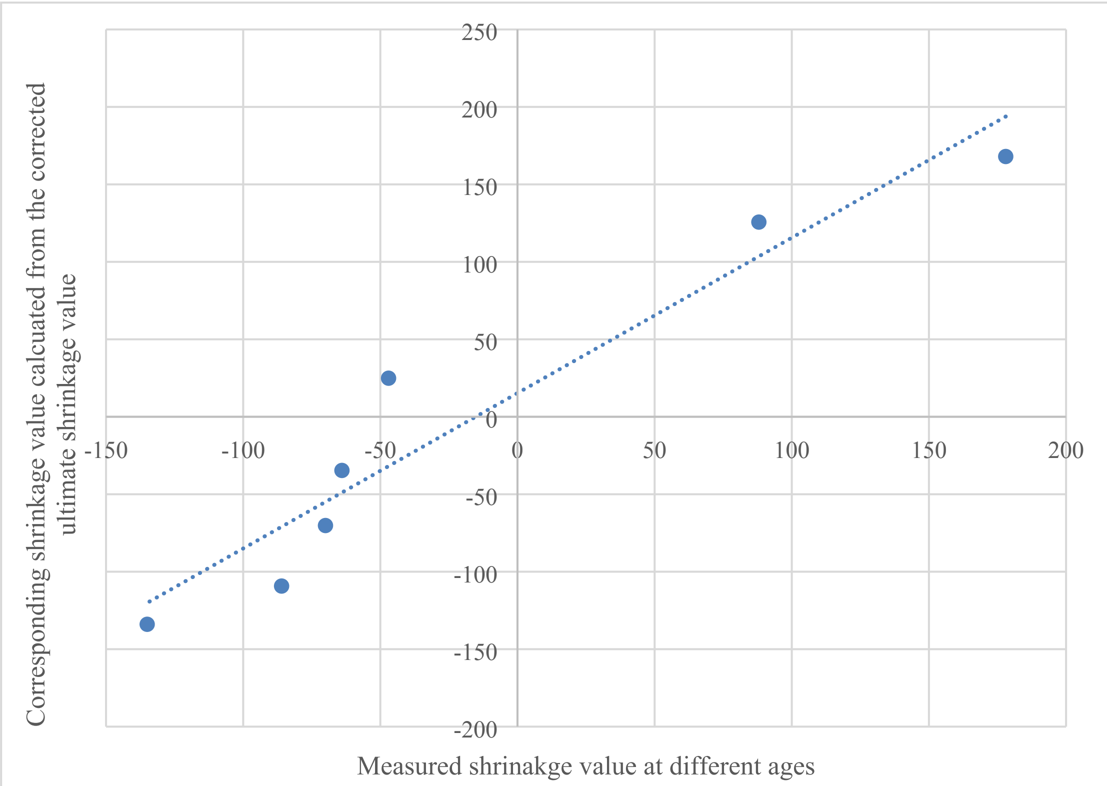

Figure 22: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 65/0/0/35

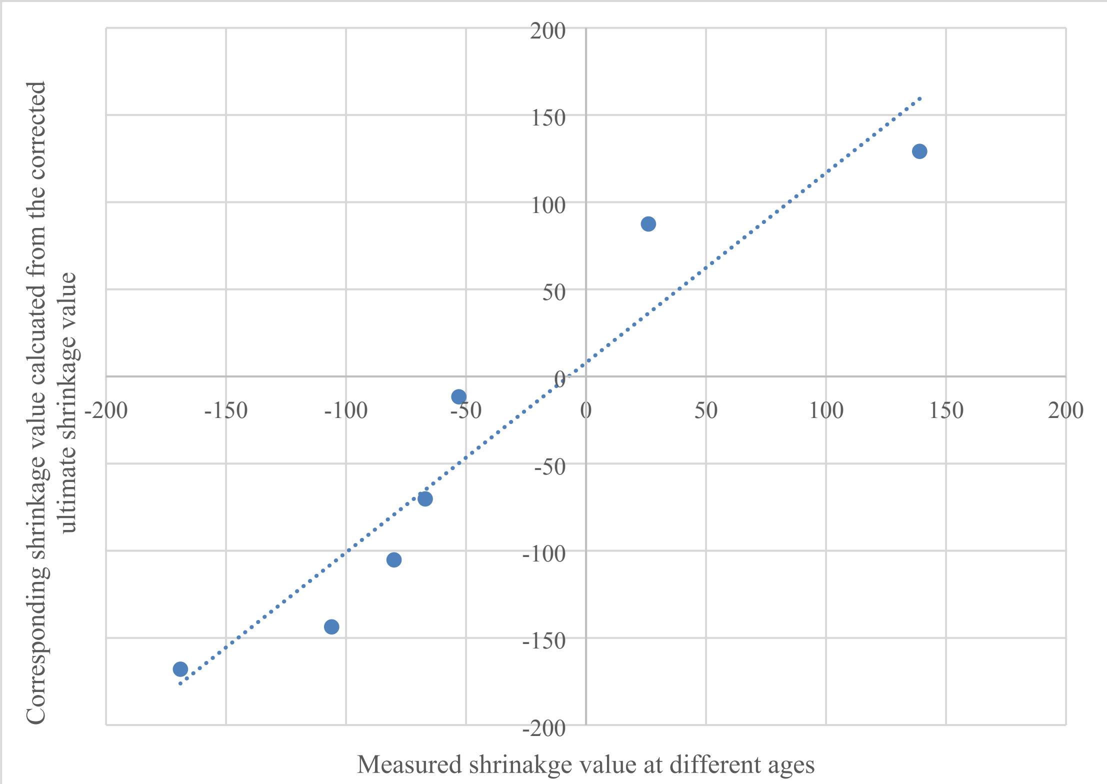

Figure 23: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 35/0/0/65

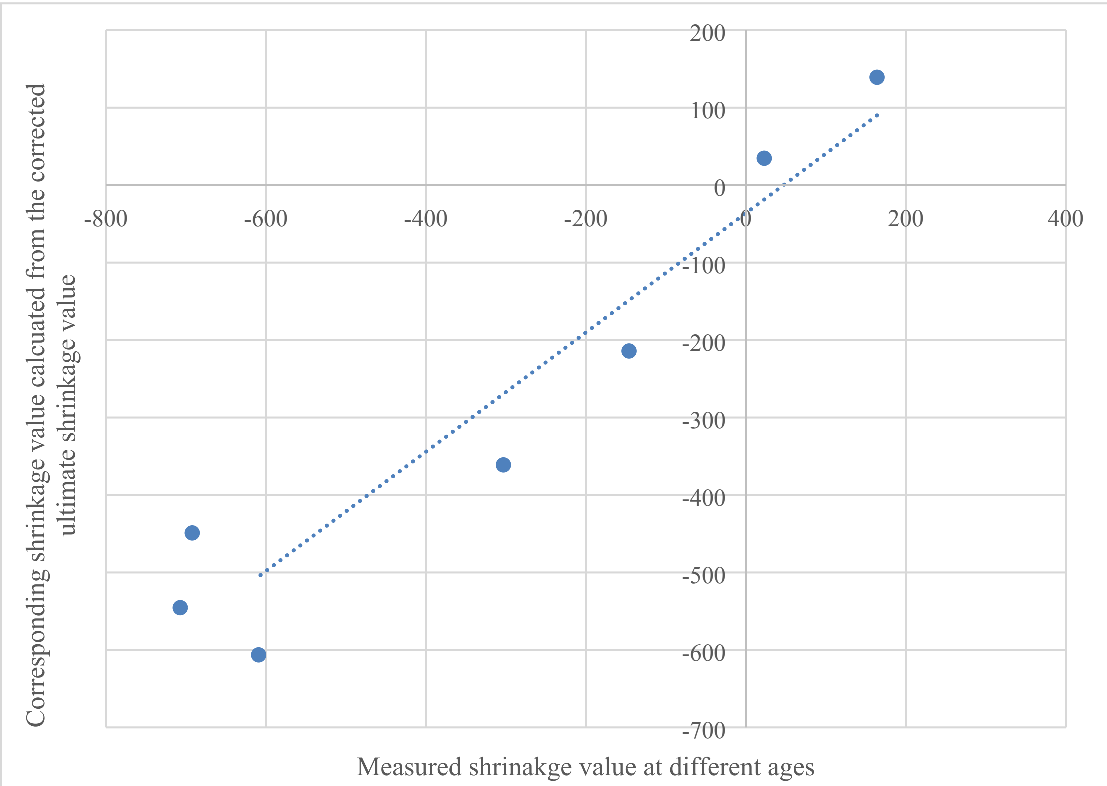

Figure 24: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 32.5/32.5/0/35

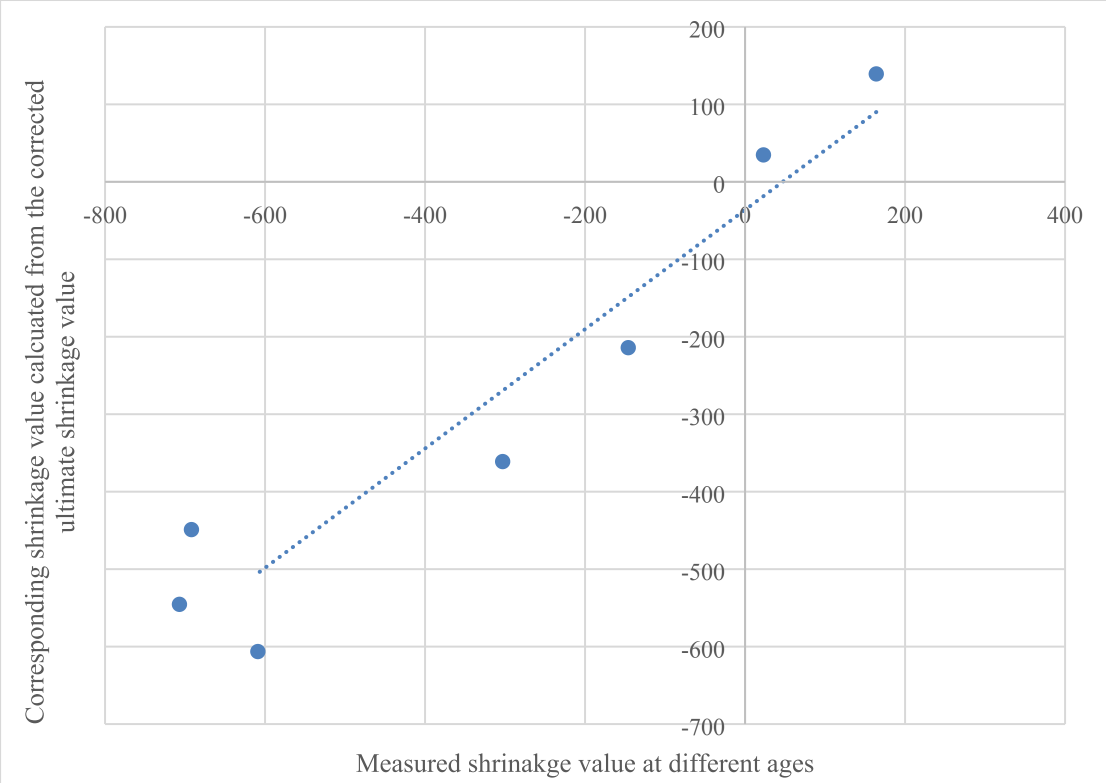

Figure 25: Correlation between MSVs and corresponding SV/C-USV at different ages for Mix 17.5/17.5/0/65

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