*K.Kawaai Int. Journal of Engineering Research and Application www.ijera.com*
*ISSN : 2248-9622, Vol. 8, Issue5 (Part -II) May 2018, pp34-41*

RESEARCH ARTICLE OPEN ACCESS

# Restrained Early Age Shrinkage At The Vertical Interface Between Freshcementitious Mixtures And Hardened Substratespart-I

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**ABSTRACT**:Casting fresh cementitious materials against a hardened concrete substrate is common for most concrete constructionin repair and retrofitting, leading to cold-joints or construction joints. The potential for problems to arise may be exacerbated when high performance concretes with a lower water-to-cementitious ratio (w/c) is used particularly when restrained early age shrinkage and subsequent drying shrinkage occurs. Such shrinkage may result in micro-racking especially at an interface that is vertically formed between the two cementitious materials, leading to durability issues and premature loss of serviceability. This experimental study in Part I has examined how restrained early age shrinkage may affect crack formation at the vertical interface formed between freshly cast cementitious mixtures and hardened concrete substrates in a tropical indoor environment (30±0.5ºC and RH of 65±2%) using the image analysis technique. The investigation has revealed that both moisture loss through water absorption via substrates andtemperature rise at an early age during cement hydration was evidently higher with larger micro-cracks being observed at the vertical interfaces of the specimens tested.

**Keywords:**Restrained early age shrinkage, Vertical interface, Moisture loss, Image analysis

Date of Submission: 03-05-2018 Date of acceptance: 19-05-2018

## I. INTRODUCTION

Shrinkage or volume change of cementitious materials is inevitable and has to be taken into account especially for low w/c ratio cementitious mixtures in order that serviceability and durability requirements are satisfied. The phenomenon commences immediately after cement hydration occurs, at times during concrete mixing, and in general shortly after finishing operations. Such shrinkage, termed early age shrinkage is commonly defined as shrinkage that takes place during the first day i.e. 24 hours, while the concrete is setting and starting to harden[1]. At such very early ages, the concrete is still fresh and there are acknowledged difficulties in the monitoring of shrinkage of such semi-solid cementitious materials. Various tests have been proposed to monitor earlyage shrinkage under a range of test and environmental conditions. Examples include testing under ideal conditions to facilitate monitoring of autogenous shrinkage and use of test specimens that are not restrained, etc.[2]. In practice, fresh cementitious materials are cast against hardened concrete substrates in repair and retrofitting, resulting in restraint at the interface between the two materials. Changes in temperature and RH, and exchanges of free water through the interface between the two materials are also known to be major influencing parameters of the phenomenon. Restrained shrinkage development in concrete has been intensively studied in past decades [3-6].Among the studies, Kyaw[7]reported on using the image analysis technique to monitor early age shrinkageat the interface between a hardened concrete substrate and freshly cast cementitious mixtures using prism specimens. The interface was vertical and only the top trowelled surface of the specimens was monitored.The measurement was started as early as 30 minutes after mix water was add. The technique was modified to measure differential shrinkage development with depth from the top trowelled surface of fresh cementitious mixtures cast onto a horizontal interface against a hardened substrate [8]. The shrinkage of the freshly cast cementitious mixtures was observed to vary with depth from the top trowelled surface especially if the specimens were unsealed. Both utilized the image analysis technique [6] with targets embedded in the freshly cast cementitious materials to enable continuous monitoring of shrinkage development at very early ages together with targets glued onto the hardened concrete substrates. According to past research, the top layer in the vicinity of the trowelled surface tends to show higher shrinkage compared to deeper zones especially if the top trowelled surface is unsealed[9]. Therefore,when cementitious materialsare cast against a hardened concrete substrate surface that is vertical, the restrained early age shrinkage taking place at the interface may exacerbate cracking near to or at the surface layer of the vertical interface.Fromthe point of view of durability and serviceability e.g. air and water tightness, the above is highly detrimental tolong-term service life[5].

## II. IMAGE ANALYSIS OF EARLY AGE SHRINKAGE MEASUREMENTS

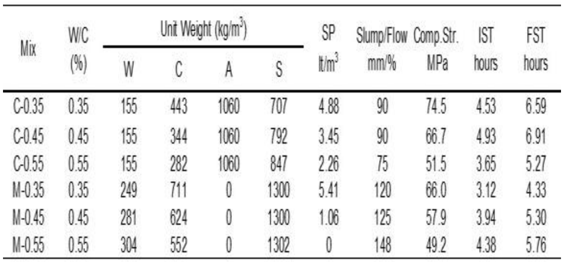
### 2.1. Monolithic Type A and composite Type B specimens (small scale)

For small scale tests, two types of specimens, Types A and B were tested. Timber molds were used to cast Type A and Type B specimens of cross section, 100 mm by 100 mm and length 300 mm or 500 mm for Type A and Type B respectively. The 300 mm long Type A specimens were monolithic specimens cast with the C-0.35 concrete mixture with a w/c ratio of 0.35 as shown in Table 1 in timber molds. For Type B specimens, hardened concrete substrates, each of size 100 mm by 100 mm and 100 mm long were first cast at both ends in partitioned timber molds. The concrete substrate cast using the C-0.35 mixture was compacted on the vibration table, trowelled and cured under indoor ambient conditions for 7 or 28 days before fresh cementitious mixtures were cast against it. The substrates were kept under plastic cover at ambient indoor conditions maintained at 30±0.5ºC and RH of 65±2%. Upon reaching the desired ages of curing, the timber partitions were removed and the selected fresh cementitious mixtures were then cast, compacted and trowelled as described previously. The latter freshly cast cementitious mixture occupied the middle 300 mm long segment of the 500 mm long Type B composite specimens. Teflon sheets with 1 mm thick were used to line the interior surfaces of the timber molds. These were left in place to reduce effects of friction. The timber partitions were removed prior to casting of the freshly cast cementitious mixtures. The middle segment of the Type B specimens was cast using either concrete or mortar mixtures, each with w/c ratios of 0.35, 0.45 or 0.55 as shown in Table 1.

The 300 mm long monolithic Type A specimens without hardened concrete substrates were tested under "sealed" or "unsealed" condition. For sealed Type A specimens, the top trowelled surfaces of the C-0.35 mixtures were covered with a layer of cling film immediately after trowelling, they were immediately placed in the environmental chamber for shrinkage monitoring to begin. The sealed surface is to minimize the loss of moisture from the top trowelled surface. The intention is to simulate a relatively well cured freshly cast cementitious mixtures. In the case of "unsealed" specimens, the top trowelled surface was left uncovered after trowelling and the specimens were placed in the environmental chamber for shrinkage monitoring. The intention is to simulate a situation in which the top trowelled surface of freshly cast cementitious mixtures suffers from moisture loss at ambient indoor conditions.

As mentioned previously, in the case of the 500 mm long composite Type B specimens, selected concrete or mortar mixtures were cast against the hardened concrete substrates at both ends after the substrates were cured for either 7 or 28 days. The ages of the hardened concrete substrates were selected at 7 or 28 days. The effects of hardened concrete substrates with different strength at these two different ages were investigated.Two specimens for each case were tested to confirm consistency of results. The mix proportions, slump/flow, compressive strength at the age of 28 days and setting time of the OPC mixtures tested undercontrolled indoor environment (30 ± 0.5ºC and RH of 65 ± 2%)are shown in Table 1.

**Table 1** Mix proportions for OPC concrete and mortar mixtures



| Mix | W/C (%) | Unit Weight (kg/m$^3$) | | | | SP lt/m$^3$ | Slump/Flow mm/% | Comp.Str. MPa | IST hours | FST hours |
|---|---|---|---|---|---|---|---|---|---|---|
| | | W | C | A | S | | | | | |
| C-0.35 | 0.35 | 155 | 443 | 1060 | 707 | 4.88 | 90 | 74.5 | 4.53 | 6.59 |
| C-0.45 | 0.45 | 155 | 344 | 1060 | 792 | 3.45 | 90 | 66.7 | 4.93 | 6.91 |
| C-0.55 | 0.55 | 155 | 282 | 1060 | 847 | 2.26 | 75 | 51.5 | 3.65 | 5.27 |
| M-0.35 | 0.35 | 249 | 711 | 0 | 1300 | 5.41 | 120 | 66.0 | 3.12 | 4.33 |
| M-0.45 | 0.45 | 281 | 624 | 0 | 1300 | 1.06 | 125 | 57.9 | 3.94 | 5.30 |
| M-0.55 | 0.55 | 304 | 552 | 0 | 1302 | 0 | 148 | 49.2 | 4.38 | 5.76 |

C-XXX: Concrete mixes, M-XXX: Mortar mixes, W: Water, C: Cement, A: Aggregate, S: Sand, SP: Super Plasticizer, IST: Initial setting time, FST: Final setting time

Coarse aggregates used were crushed granite with a maximum size of 20 mm with a specific gravity of 2.60. Fine aggregates used were natural sand with a specific gravity of 2.60. High range water reducing admixture (SP) was added to the mixtures to obtain adequate workability. In addition, three 100 mm cubes for each batch of concrete mixtures and 50 mm cubes for mortar mixtures were also cast for compressive strength tests. The setting times of the mortar fraction of concrete mixtures and mortar mixtures were determined using the penetration resistance test in accordance to ASTM C 403-08 [10], the workability was determined by the slump test in accordance to ASTM C-143-10a [11] and the flow test was conducted in accordance to ASTM C-1437-07 [12]. The moisture loss and temperature development with time were measured for the entire duration of the experiments. The temperature was monitored using thermocouples connected to data loggers as shown in Fig. 1, and the change in mass (moisture loss) was monitored by placing the specimens on a weighing scale with 0.1 g sensitivity during monitoring of the shrinkage under controlled indoor environmental conditions (30 ± 0.5ºC and RH of 65 ± 2%).

Shrinkage strains of freshly cast cementitious mixtures and concrete substrate were monitored using a set-up similar to that as detailed by Ong and Chandra [8]. The technique monitors the movement of pairs of targets inserted from the top and side of the specimens. The targets comprise 1.5 mm diameter steel pins topped by plastic discs and inserted into the specimen immediately after casting through the full depth or through the breadth of the specimens. Cameras were then set up as shown in Fig.1 and the first images of the targets were captured as early as 30 minutes after adding water to cementitious mixture. Further images were then captured at predetermined time intervals and processing of the positions of the targets enabled the shrinkage strains to be monitored. Top and side mounted cameras monitored the movement of the 4 mm square inked targets on top of each plastic disk. Image acquisition, filtering, segmentation and binary image processing operations are major processes undertaken in the analysis of the images captured. Shrinkage between a pair of targets can be calculated by quantifying the length change over the original gauge length over a certain time interval starting at the time zero value (TZV). Ong and Kyaw [6] reported that the accuracy of the present test set-up would be in a range of ±20 µm/m andmore details of the test methodology may be found elsewhere [7-9]. The size of holes where steel pin targets were installed from the side of the specimens was large enough for the targets to move along with the freshly cast cementitious mixtures as they hardened and shrank. Targets on the hardened concrete substrates were glued on with fast setting epoxy resin adhesives.

Fig.1 shows a schematic diagram of the test set-up. The shrinkage strains at different depth were monitored with targets located at distances of 10, 35, 60 and 85 mm from the top trowelled surface of the specimen. As shown in Fig.1, rectangular timber wedges attached by screws to the sides and base of the timber molds, anchored the substrate segments to the timber molds. Three sets of targets were mounted on the two hardened concrete substrate segments at both ends of each specimen. The targets were glued using epoxy resin adhesive to the hardened substrate at a distance of 10 mm from the interface between the substrates and freshly cast cementitious mixtures. Also shown are two series of targets (S-1 to S-4 and S-5 to S-8) inserted through the full breadth of the each specimen. The S-1 to S-4 targets were located at a distance of 10 mm from the interfaces between the substrate and freshly cast cementitious mixtures, starting from S-1 at a depth of 10 mm from the top trowelled surface of the specimen, S-1 to S-4 were placed 25 mm apart, depthwise. Thus S-4 was located 85 mm from the top surface. In the case of targets S-5 to S-8, these were located at a distance of 60 mm from the interfaces between substrate and freshly cast concrete or mortar mixtures. Their positions with respect to depth from the top surface corresponded to those of S-1 to S-4. The intention was to monitor early age shrinkage of the freshly cast cementitious mixtures in the immediate vicinity of the interface between the hardened substrate and freshly cast concrete or mortar mixture as well as within the freshly cast mixture itself further away from the vertical interface. It may be noted that no target into the specimen from the top of the specimen were placed. This is intentional as earlier studies [8] have shown that the shrinkage strain obtained from monitoring using targets similar to the S-1 and S-5 targets mirror the early age shrinkage strains monitored by targets inserted into the top trowelled surface of the test specimens.The measurement of shrinkage was carried out using the same methodology as described in Section 2.1. Type B is intended to simulate a probable scenario in precast concrete or in patch repair method, viz., cementitious mixtures cast against unreinforced hardened concrete substrates. Two specimens in the case of Type A and Type B were tested to confirm

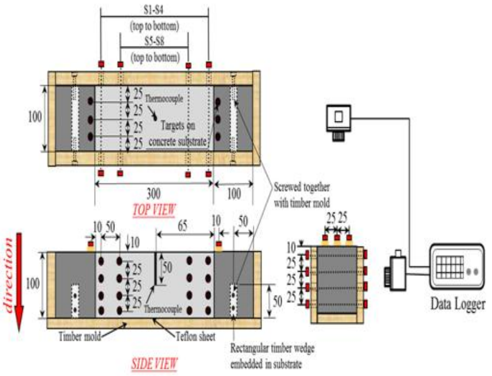
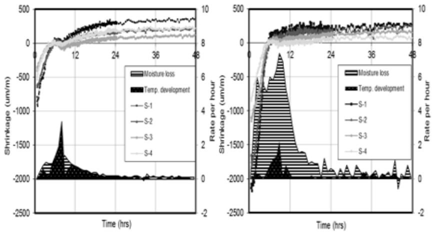


Fig. 1 Details of Type B specimens and schematic diagram of test set-up

consistency in the test results.



(a) (b)

Fig. 2 Type A specimens for the C-0.35 mixtureunder(a): “sealed” and (b): “unsealed” conditions monitored up to 48 hours

## III. RESULTS AND DISCUSSION FOR TYPE A AND B SPECIMENS

### 3.1.OPC C-0.35 mixtures under “sealed” and “unsealed” conditions (Type A)

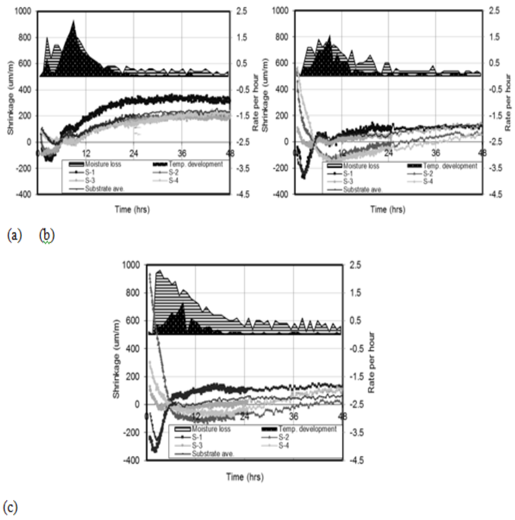
Fig.2(a) and 2(b) show the shrinkage strains of two Type A monolithic specimens cast with the C-0.35 mixture, monitored using the image analysis method, starting 30 minutes after adding water to the mixture under “sealed” and “unsealed” conditions respectively. Also shown is the moisture loss and temperature readings monitored within the specimen. The rate of moisture loss and temperature monitored is plotted as the change in weight (g) and change in temperature (°C) within each consecutive one hour interval from the start of monitoring. The shrinkage strains are plotted with the initial setting time chosen as the TZV.

As mentioned previously the specimens were placed in the environmental chamber (30±0.5ºC and RH of 65±2%) throughout the 48 hours of monitoring. As expected the unsealed specimen registered higher moisture loss and lower peak temperature compared to those of the sealed specimen. As the temperature rose due to heat evolution from cement hydration, significantly higher moisture loss occurred mainly from the exposed trowelled surface of the unsealed specimen. In contrast, the moisture loss from the sealed specimen was much smaller. However the seal is not intended to be perfect and moisture loss was minimal owing to the cling film applied onto the trowelled surfaces of the specimens. The temperature rise of the freshly cast C-0.35 mixture increased in the case of “sealed” specimen. The peak temperatures of the C-0.35 mixture occurred after 8.3 or 9.0 hours for “sealed” or “unsealed” specimens respectively. The initial setting time as shown in Table 1 was about 4.5 hours.In addition to the substantially higher moisture loss, a significant amount of early age shrinkage took place even before the initial setting time. The early age shrinkage strain reached 2175 µm/m from 30 minutes after water was added to the mix to the initial setting time of the mix. Compared to the S-1 targets, the early age shrinkage strains registered by the S-2 to S-4 targets were about 83, 53 and 37% of the S-1 shrinkage strain over the same monitoring duration. Fresh mixtures at depths deeper than 60 mm from the trowelled surface registeredsubstantially lower shrinkage strains compared to those at top layer. For the case of “sealed” specimens, the shrinkage strain registered by the S-1 targets was 924 µm/m which was about 30% of the strain registered by the “unsealed” specimen. The early age shrinkage strains registered by the S-2 to S-4 targets were about 66, 57 and 44% of shrinkage strain observed at the corresponding S-1 targets. It indicates smaller variation of shrinkage strains with depth from the trowelled surface in the case for “sealed”specimens. The peak temperature reached was 39.2 or 35.3ºC for the “sealed” or “unsealed” specimens occurring after 8.3 and 9.0 hours respectively. Similarly, the maximum rate of moisture loss,viz.1.4 and 7.4 g per hour for “sealed” or “unsealed” specimens occurred between 8 to 9 hours after mixing water was added to the mixtures. The peak temperature or the maximum rate of moisture loss was observed some 3.5 to 4.5 hours after the initial setting time of the C-0.35 mixture. The results suggest that the maximum rate of moisture loss is caused by the heat evolution from cement hydration in the freshly cast C-0.35 mixture.

### 3.2. OPC C-0.35, 0.45 and 0.55 mixtures freshly cast against hardened concrete substrates at the age of 7 or 28 days (Type B)

Fig.3(a),3(b) and 3(c) show results of early age shrinkage monitoredstarting 30 minutes after adding water to the mixture up to 48 hours later for Type B composite specimens cast with the C-0.35, 0.45 and 0.55 mixtures respectively. As mentioned previously the end segments were cast using the C-0.35 mixture. The hardened substrates were cured for 7 or 28 days under ambient indoor environment before casting of the middle segment. These specimens were sealed specimens, i.e. the top trowelled surface was covered with a layer of cling film before the specimens were placed in the environmental chamber prior toshrinkage monitoring. Also shown are the hourly moisture loss (g per hour) and temperature readings (°C per hour) monitored over the same duration. As can be seen, respective pairs of targets inserted in the freshly cast mixtures moved apart, towards the hardened substrate i.e. expansion was observed before the initial setting time. This expansion phase was later followed by shrinkage and took place for the longest time duration in the case of the specimen cast using the C-0.55 mixture. The early age shrinkage strains registered bythe S-1 to S-4 targets in the case of the C-0.35 mixture were 342, 256, 147 and 223 µm/m respectively. Compared to those of Type A specimen under "sealed" conditions, the magnitude of shrinkage strains was not observed to be higher in the case of Type B specimen. However, both registered the highest early age shrinkage strains at the S-1 targets and progressively lower strains with depth, i.e. S-2 and S-3 targets. Shrinkage strains of theS-4 targets were marginally higher than that of S-3 targets. The major difference between Type A and Type B specimens may be illustrated by their behavior before the initial setting time. The concrete mixtures in Type A specimen registered consistent shrinkage strains over the initial period of shrinkage monitoring, in contrast the concrete mixtures in Type B specimen showed expansion or negative shrinkage initially before progressing to positive shrinkage.

As can be seen in Fig.4a, 4b and 4c, the expansion phase was more apparent as the w/c ratio increased. The maximum moisture loss of each mixture occurred between 9 to 10, 5 to 6 or 2 to 3 hours for the C-0.35, C-0.45 and C-0.55 mixtures respectively. The maximum hourly moisture loss was about 1.5, 1.4 and 2.3 g per hour respectively. The C-0.55 mixture indicated substantially higher moisture loss, which tends to occur well before the initial setting time.In contrast to the C-0.55 mixture, the C-0.35 specimens registered the maximum rate of moisture loss during which the temperature peaked after the final setting time. Besides the larger moisture loss occurringbefore the initial setting time, the peak temperature of the C-0.55 mixture was the lowest among the mixtures tested. The peak temperature reached 38.4, 36.2 and 34.8ºC, occurring after 9.6, 8.9 and 9.1 hours for the C-0.35, C-0.45 and C-0.55 mixtures respectively. The higher temperature observed for the C-0.35 mixture was due to the increased amount of cement present in the mixtures, thus generating more heat during hydration. It is worth to note that the expansion phase was extended over a longer duration even exceeding the initial setting time especially for the mixtures with the higher w/c ratio of 0.55. The prolonged expansion was observed especially at deeper targets for the C-0.45 and C-0.55 mixtures. This was accompanied by moisture loss which continued to take place until 8.6, 9.2 and 11.1 hours later for the C-0.35, C-0.45 and C-0.55 mixtures respectively.



(a) (b)

(c)

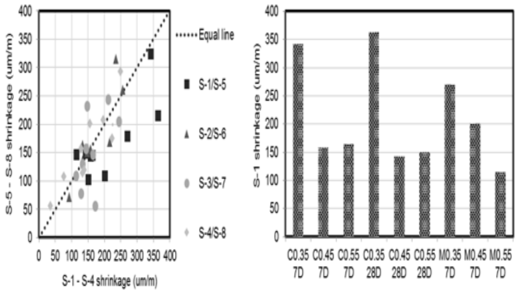
As reported by past research [9], the highest shrinkage strain was observed at the S-1 targets placed nearest the top trowelled surface and close to the interface particularly for the mixture with a w/c ratio of 0.35. Other targets placed at deeper zones registered consistently lower shrinkage strains than that of the S-1 targets. The temperature rise of the freshly cast concrete mixtures increased as the w/c ratio decreased, whereas the moisture loss possibly through the interface via suction forces especially in the deeper zones was significant in the case of the specimen freshly cast with theC-0.55 mixture. The magnitude of the shrinkage strains obtained in each mixture indicates possibility of cracking especially at the vertical interface formed between the freshly cast concrete mixtures and hardened concrete substrates. However, it may not be conclusively confirmed usingonly the magnitude of shrinkage strains of the freshly cast mixtures. Crack formation accompanied by concurrent movement of substrates along with early age shrinkage shouldbe preferably quantified.

As can be seen, effects of hardened concrete substratesduring its expansion phase immediately before the initial setting time was more significant in the case of mixtures with a higher w/c ratio of 0.55. Larger expansion for higher w/c ratio mixtures may be attributed to larger moisture loss most probably through the interfaces formed to the substrates at early stages, especially free water in the case of the mixture with a higher w/c ratio i.e. the C-0.55 mixture. The latter registered more prolonged moisture losses, expected to continue beyond 48 hours. The shift from the initial expansion phase to subsequent shrinkage development tends to occur firstly in the targets closer to the top trowelled surface followed later by targets further away, depthwise. For all the mixtures tested, the targets on the substrates moved inwards towards the interfaces as the freshly cast cementitious mixtures registered early age shrinkage. For the C-0.35 and C-0.55 mixtures, after their initial setting times the concurrent movement of the targets placed on the substrates seems to reach steady-state. The difference in the shrinkage magnitudes registered by the targets placed on the substrate and the S-1 targets seemed to show a constant value well before 48 hours after adding water to the mix. This difference was observed to be clearly smaller in the case of the C-0.45 mixture. This was also confirmed by observations made which showed that the crack width measured was the smallest in the immediate vicinity of the vertical interface in the C-0.45 specimens. Cracks at the vertical interfaces appear to develop immediately after initial setting time when the tensile strain capacity is low and it progressively grew registering widths ranging from 7 to 70 µm. Based on the observations made after 48 hours of the shrinkage monitoring, the crack formation was localized in the vicinity of vertical interfaces. As data was logged automatically, when the cracks initiated could not be captured using the present test set up. This was not unexpected given that the S-1 to S-4 targets were installed 10 mm away from the vertical interfaces.

The early age shrinkage depends largely on temperature rise and moisture loss during the first 48 hours as shown in Fig.3(a), 3(b) and 3(c)for the concrete mixtures with different w/c ratios. Both were evidently higher for specimens withw/c ratios of 0.35 and 0.55, cracks that developed up to 48 hours later are more likely to be wider especially if the interface is vertical. The C-0.45 specimens clearly registered better performance with regards to potential for cracking at the vertical interface. According to past research, when the w/c ratio of a cementitious mixture is below 0.42, the paste will self-desiccate [13].Since water is physically lost especially through the vertical interface via absorption by the hardened concrete substrate in this study, the effective minimum w/c ratio needed to avoid self-desiccation is expected to be slightly higher than 0.42. If the w/c ratio is less than 0.42, the autogenous shrinkageas defined by the Japan Concrete Institute [14] is prominent as illustrated by the results obtained for C-0.35, while drying shrinkage will be more significantif the w/c ratio is higher than 0.42, as illustrated by the results obtained for the C-0.55 mixture. Therefore, it is postulated that an optimum ratio to reduce the potential for cracking could lie between the w/c ratio of 0.4 to 0.5 for this particular testing configuration. Further tests would be needed to confirm this and to arrive at a w/c ratio foroptimal performance especiallywhen the test parameters and environmental and exposure conditions are different from those used in the present study.

### 3.3. Effects of the presence of hardened concrete substratesthroughthe monitoring of temperature development and moisture loss

Comparison of shrinkage strains monitored at the S-1 to S-4 targets close to the vertical interfaces and the S-5 to S-8 targets at the interior zones for the concrete and mortar mixtures with w/c ratios ranging from 0.35 to 0.55 is shown in Fig. 4(a). Ages of the substrates were 7 or 28 days curedunder ambient indoor environment, 30 ± 0.5ºC and RH of 65±2%. The figure suggests that the shrinkage strains registered by the S-1 targets closest to the top trowelled surface registered significantly higher values than those of the interior zones. The freshly cast cementitious mixtures tend to show higher shrinkage strains especially at the surface layers,which could be attributed to larger moisture loss through absorption of free water by the substrates. However, the shrinkage strains registered by the deeper targets placed in the vicinity of the vertical interfaces may be comparable to those further away from the interfaces. The influence of ages of the substratesalso seems to be less significant in terms of the magnitude of early age shrinkage strains, as can be seen in Fig. 4(b). The magnitude of the early age shrinkage strains observed in the fresh cementitious mixtures cast againstconcrete substrates at the age of 7 and 28 days respectively were comparable for the both cases. For the mortar mixtures, the magnitude of the shrinkage strains increased consistently as the w/c ratio decreased. The increase was less apparent in the case of the concrete mixtures tested in this study.



(a) (b)

Fig. 4(a): Comparison of shrinkage strains registered by S-1 to S-4 and S-5 to S-8 targets, (b): Shrinkage strains registered by S-1 targets formortar and concrete mixtures cast against concrete substrates at the ages of 7 and 28 days under “sealed” condition

As expected, cracks tended to form near the interfaces within the freshly cast cementitious mixtures side rather than within the hardened substrates. Crack widths measured using microscope seemed to be smaller when the fresh cementitious mixtures were cast against the concrete substratesat the age of 28 days. Crack widths were generally larger as the difference between the S-1 shrinkage strains and that of the substrates increased. For the OPC concrete mixtures tested, the smallest crack width was observed in the case of the C-0.45 mixture specimens, whilelarger cracks were observed in the C-0.35 mixture specimens.

### 3.4. Comparison of shrinkage strains (S-1 to S-4 targets) developed between initial setting time to 24 hours and 24 to 48 hours for OPC mixtures

Fig. 5 shows the ratios of shrinkage strains registered by the S-1 to S-4 targets developed for the first 24 hour duration between initial setting time to 24 hours, and for the second 24 hour duration, 24 to 48 hours, ofshrinkage monitoring. The former was calculated on the basis of minimum shrinkage strains registered after the initial setting time, which were often negative shrinkage (expansion) strains. As can be seen especially in the case of the C-0.35 mixture, the shrinkage strains registered by the S-1 targets comprised mainly the strains developed within the first 24-hour duration. This indicates that some of the free waterseemed to have evaporated faster near the surface layer of the freshly cast cementitious mixtures in the vicinity of the vertical interfaces.

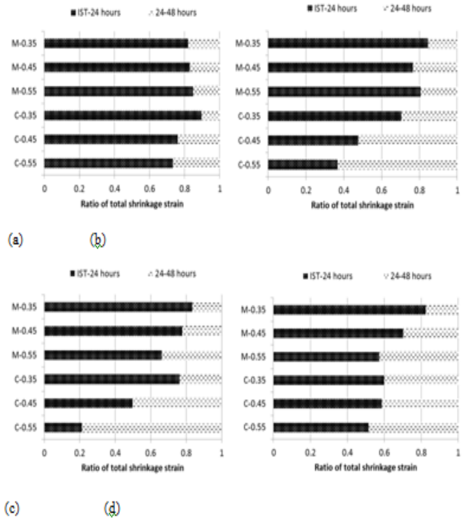


Fig. 5Ratios of the S-1 (a), S-2 (b), S-3 (c) and S-4 (d) shrinkage strains developed for OPC mixtures between initial setting time to 24 hours and 24 to 48 hours of shrinkage monitoring under “sealed” condition

Theshrinkage developed by the cement hydration during the subsequent 24 hours duration of shrinkage monitoring is significant especially with depth, with increasing w/c ratios of the freshly cast mixtures. Although most of the S-1 targets in the OPC mixtures registered higher ratios of the total early age shrinkage strains during the first 24 hours ofshrinkage monitoring, the shrinkage strains registered at deeper zones appear to develop forlonger time duration and are expected to continue after 48 hours. This could be attributed to the moisture left in the specimens under “sealed”condition and the subsequent loss of moisture through absorptionby the vertical interfaces. In addition, the initial setting time may also beinfluencing how early age shrinkage strains develop with depth. It should be noted that initial setting time of the C-0.55 was later than that of the C-0.45 mixture although the penetration resistance test result of the C-0.55 mixture showed the shortest time among the OPC mixtures as shown in Table 1. It can be said that as the initial setting time increases, the ratio of the shrinkage strains developed for second 24-hour duration of shrinkage monitoring increases with depth from the top trowelled surface.

As can be seen, the prolonged shrinkage development is more significant in the concrete mixtures with higher w/c ratios. In particular, the effect is substantially higher in the case of the C-0.55 mixture, thus indicating thatshrinkagecontinues to develop owing to prolonged moisture loss from the “sealed” specimens through absorption by the vertical interfaces especially at deeper zones. The S-2 to S-4 targets in the C-0.55 mixture showed higher ratios (>40%) ofshrinkagedevelopmentduring the second 24 hour duration ofshrinkage monitoring. The results seem to suggest that the prolonged shrinkage development could be even more significant in large sized specimen at deeper zones if much free water is available within the specimen under “sealed” conditions, which is discussed in Part-II.

## IV. CONCLUSIONS

Early age shrinkage of fresh cementitious mixtures cast against hardened concrete substrate using image analysis wasexamined. The investigation has revealed how heat evolution and moisture loss occurring within the test duration of 48 hours after adding water to the mixture may affect the shrinkage at an early age. The results on monolithic Type A specimens showed that very high early age shrinkage strains occur with cementitious mixtures with the lower w/c ratio of 0.35. This is exacerbated if there is significant moisture loss from the top trowelled surface, as in situations when curing conditions are less than ideal. In better cured, sealed specimens, shrinkage was relatively uniform across the whole cross section. In the case of Type B composite specimens the potential for cracking at the vertical interface between the hardened concrete substrate and the freshly cast cementitious mixtures can be controlled by lowering the temperature rise and moisture loss from the newly cast mixture through the vertical interface. The results suggest that both temeprature development and moisture loss (hourly rates) during the early stage of cement hydration was evidently higher with larger cracks being observed at the vertical intrefaces of the test specimens under the indoor environmental condition.

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