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Restrained Early Age Shrinkage at the Vertical Interface Between Freshcementitious Mixtures And Hardened Substratespart-II

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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 II has examined the size effect of early age shrinkage under "sealed" condition in larger size specimens.The results show that the duration during whichdevelopment of early age shrinkage is accompanied by moisture loss through the interfacescan be expected to continuefor a longer duration typically, beyond 24 hours after adding water to the mix. The strategy to minimizing micro-cracks through reducingheat evolution and moisture loss through the interface simultaneously was found to be particularly effective in large sized specimen.

Keywords: Early age shrinkage, Image analysis, Vertical interface, Size-effect

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I. INTRODUCTION

In precast concrete or renewal construction connected to existing buildings, it is common to cast fresh cementitious mixtures against a hardened concrete substrate especially at in-situ joints and connections [1,2]. At such joints and connections it is usual to cast low w/c ratio cementitious materials against hardened concrete substrates. If the interface is vertical and if curing is not properly carried out, the undesirable effects of early age shrinkage accompanied later by drying shrinkage in the vicinity of the interface will be even more significant[3]. However, the amount of early age shrinkage depends on various factors, including properties of cementitious mixtures, temperature, relative humidity of the macroscopic and microscopic environment, and degree of restraint. In addition, laboratory scale tests usually involving rather small specimens may not be able to simulate actual behavior taking place in larger sized specimens.Weiss et al. [4] reported on experimental evidence to show that a size/geometry dependence is observed in the shrinkage cracking behavior of restrained concrete structures.

In the present study reported, a series of tests were conducted on test specimens including small scalemonolithic and composite specimens in Part-I and larger prototype specimens in Part-II. Crack formation in the vicinity of the interface between the hardened concrete substrates and freshly cast cementitious mixtures was investigated experimentally in tandem with early age shrinkage monitoring using the image analysis technique as detailed by past research [5].

II. IMAGE ANALYSIS OF EARLY AGE SHRINKAGE MEASUREMENTS

2.1. Materials

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 [6], the workability was determined by the slump test in accordance to ASTM C-143-10a [7] and the flow test was conducted in accordance to ASTM C-1437-07 [8]. 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.

2.2. Prototype Type C specimen (large scale)

Type C specimens were of cross section 300 mm by 300 mm and length 500 mm. The two end segments, each of cross section 300 mm by 300 mm and length 100 mm, comprised hardened concrete substrates cast using the C-0.35 mixture as shown in Table 1. Embedded at the bottom, placed centrally as shown in Fig.1 is a fabricated steel section (mild steel plate, ASTM A36) with one end each cast embedded in the hardened concrete substrate segment at both ends. The central 300 mm long segment was cast using one of the 6 concrete or mortar mixtures as shown in Table 1. The concrete substrate segments with the structural steel section were first cast with timber partitions placed in the timber mold. The substrate was compacted using mold vibrators, trowelled and cured for 7 daysunder ambient indoor environment. The specimens were covered with plastic sheets and maintained at 30±0.5ºC and RH of 65±2%. As mentioned

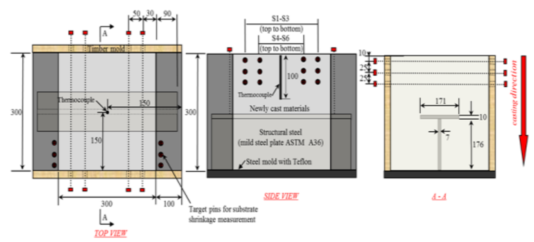


Fig. 1 Composite Type C specimens comprising structural steel, hardened concrete substrates and freshly cast cementitious mixtures

previously all interior surfaces of the timber molds were lined with Teflon sheets. After curing the substrates for 7 days the timber partitions were removed and the selected concrete or mortar mixtures were placed in the central 300 long segment. After compaction and trowelling, the top surface was wrapped with a layer of cling film (sealed condition) and the specimens were placed in the environmental chamber as mentioned for shrinkage monitoring. The measurement of shrinkage was carried out using the same methodology as described in Section 2.1 in Part-I. Type C specimen is intended to simulate a probable scenario in precast concrete, viz., cementitious mixtures cast against hardened concrete substrates in which a structural steel section may be embedded. As the test specimens in the case of Type A monolithic and Type B composite specimens showed consistency in test results in Part-I, only 1 specimen each was tested in the case of Type C composite specimens.

III. RESULTS AND DISCUSSION FOR PROTOTYPE TYPE C SPECIMEN (LARGE SCALE)

3.1. Type C specimens cast using C or M-0.35, 0.45 and 0.55 mixtures

The larger composite Type C specimens comprising hardened concrete substrates, freshly cast materials and structural steel is shown in Fig. 1. Target pins, viz. S-1 to S-6, were embedded up to a depth of 60 mm from the top trowelled surface. Fig. 2 shows shrinkage strains registered by the S-1, S-2 and S-3 targets with temperature development (°C per hour) of the freshly cast cementitious mixtures. Also shown are strains of embedded structural steel calculated using a coefficient of thermal expansion of 12 μ per °C.As observed in the smaller Type B specimens, the concrete and mortar mixtures with a w/c ratio of 0.35 registered the highest shrinkage strains, viz. 596 and 404 μm/m respectively after 48 hours ofshrinkage monitoring. The higher shrinkage strains may be attributed to the significant temperature rise arising from cement hydration at the early stages. Interestingly for the concrete and mortar mixtures with a w/c ratio of 0.55, the early age shrinkage registered by the S-1 to S-3 targets installed near the top trowelled surface, registered higher and more prolonged shrinkage development over the 120 hours of monitoring. It was noted that it took about 120 hours for the shrinkage to develop owing to water evaporation particularly in the case of the C-0.55 mixture. In contrast, in the smaller Type B specimen, the early shrinkage strains of the C-0.45 and C-0.55 mixtures were comparable. It was also noted that the shrinkage strains of the M-0.55 specimen exceeded that of the M-0.45

specimen in the Type C specimens.

Of the six Type C specimens tested, all the specimens showed a gap at the vertical interface after 48 hours. The gap across the whole of the vertical interface is most likely due to expansion of both the embedded structural steel section and freshly cast concrete or mortar mixtures due to heat generated by cement hydration followed by subsequent contraction upon cooling down. All three mortar specimens registered higher temperature rise as expected. The mortar mixture specimens also registered higher expansion or negative shrinkage strains well after the initial setting time. This is probably one of the major causesleading to the larger gaps observed at the interface. Besides the temperature rise, another major influencing parameter affecting the early age shrinkage is moisture loss. It is worth reiterating that moisture loss can occur before and after initial setting and may also occur over relatively prolonged time duration. More prolonged moisture loss under "sealed" condition is expected to result in larger loss of moisture from the freshly cast mixture, leading to higher early age shrinkage and subsequent drying shrinkage. A major observation noted is that the C-0.55 Type C specimens registered larger shrinkage strains compared to the C-0.35 specimens. This was also the case in the Type C mortar specimens. This could be due to the combined effects of both prolonged temperature development and prolonged moisture loss duration under the "sealed" condition. In the case of the smaller Type B specimens, the largest shrinkage strains were not registered by the specimens with a w/c ratio of 0.55.

3.2. Size-effect of early age shrinkage between small and large scale

Fig. 3(a) shows the early age shrinkage strains in the vicinity of vertical interfaces and interior zones. The S-1 shrinkage strains in the vicinity of vertical interfaces were mostly found to be higher, which is consistent with those observed in Type B specimens in Part-I. The difference between early age shrinkage strains registered by thefreshly cast cementitious mixtures and the movement of their corresponding concrete substrates was the smallest in the C-0.45 and M-0.45 specimens. The maximum shrinkage strains monitored in the larger Type C specimens were about 1.4 to 4.7 times those of the respective smaller Type B specimens in Part-I as shown in Fig. 3(b). This was most significant in the case of the C-0.55 and M-0.55 specimens. Therefore, the strategy of lowering temperature rise and reducing moisture loss via absorption through the vertical interface between the hardened concrete substrate and the freshly cast cementitious mixtures is still valid based on observations made in the larger Type C composite specimens. As the size of the composite specimens becomes larger the effects of both prolonged temperature rise and prolonged moisture loss duration must be taken into consideration in order to minimize the potential for cracking. The presence of the embedded structural steel section within the composite specimen also has an impact, as the steel section is prone to first expansion and subsequent contraction during the period of monitoring.

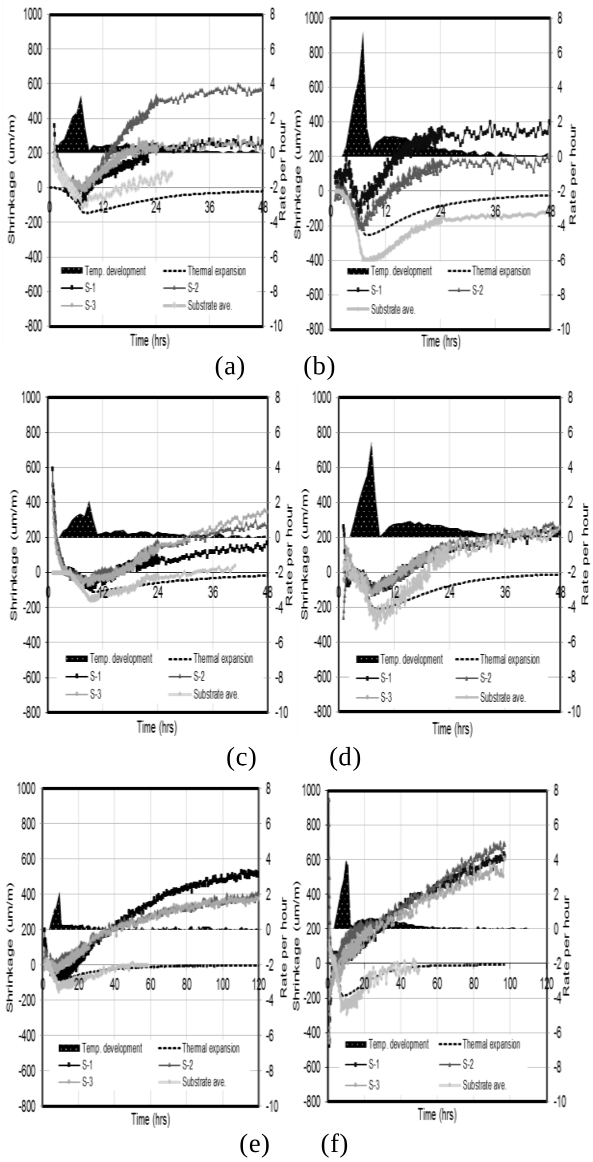
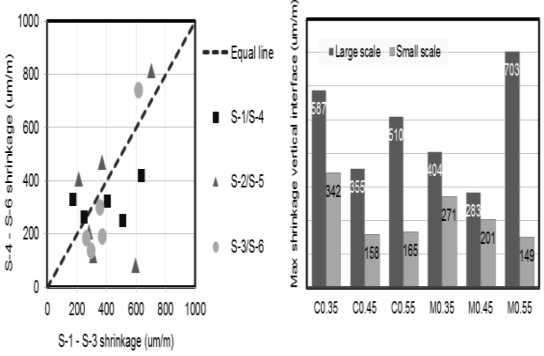


Fig. 2 Shrinkage strains of Type C specimens cast using concrete and mortar mixtures with w/c ratiosof (a, b): 0.35, (c, d): 0.45 and (e, f): 0.55 under "sealed" condition



(a)

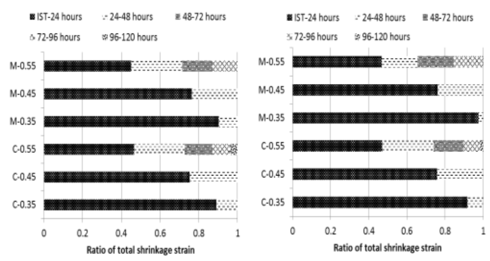
Fig. 3(a): Comparison betweenS-1 to S-3 andS-4 to S-6 shrinkage strains, (b): Maximum shrinkage strains of Type B and Type C specimens under "sealed" condition

The condition of the hardened substrate surface receiving the freshly cast cementitious mixture also affects early age shrinkage of the specimens tested. If the substrate is very dry it is reasonable to expect that it will absorb free water via capillary suction from the freshly cast cementitious mixture irrespective of whether the top trowelled surface is sealed or not. The difference in early age shrinkage observed in the case of the smaller Type B specimens in Part-I and larger Type C specimens confirms this as shown in Fig. 3(a). It should be noted that the target pins closest to the top trowelled surface is located at a depth of 10 mm from the surface. Based on studies [5] carried out earlier the values may be assumed to be representative of the shrinkage occurring at or near the top trowelled surface. Additionally, even though there was a gap present at the interface caused by the expansion and subsequent contraction of the embedded structural steel section, the shrinkage monitored in the Type C specimens seems to be attributed solely to early age and subsequent drying shrinkage of freshly cast mixtures. No correction factors were applied to account for the expansion and subsequent contraction of the structural steel section.

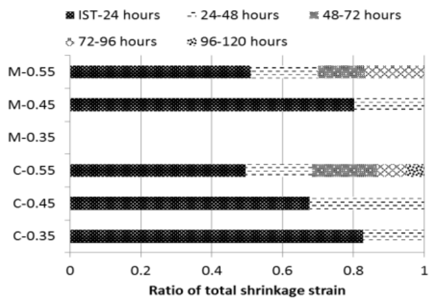
3.3. Comparison of shrinkage strains (S-1 to S-4 targets) developedin eachconsecutive24-hour intervals up to 120 hours of shrinkage monitoring

Fig. 4 summarizes the total shrinkage, both early age and subsequent drying shrinkage, monitored overa duration of 120 hours. For convenience, the shrinkage strains monitored is divided into shrinkage monitored during consecutive 24 hour intervals up to 120 hours of monitoring for the concrete and mortar mixtures with a w/c ratio of 0.55. This was done to facilitate observations made regarding testing of Type C specimens as the early age shrinkage seems to occur for durations longer than 24 hours after adding water to the mix before subsequent drying shrinkage assumes primacy. For the case of the smaller Type B specimens in Part-I, almost all the mixtures tested registered more than 70% of the total shrinkage strain within the first 24 hour duration. In fact, all the mortar mixtures and the C-0.35 mixture registered higher ratios, well over 80% of the total shrinkage strain especially at the S-1 targets in the vicinity of the top trowelled surface.

As observed in Fig. 4(a),4(b) and 4(c), the shrinkage strainsoccurring during the first 24 hour interval for the concrete and mortar mixtures with w/c ratios of 0.35 and 0.45 weremore than 70% of the total strain [$\varepsilon_{24}/\varepsilon_{48}$]. However, some targets inserted into the C-0.55 and M-0.55 mixturespecimens registered ratios less than 70% of the total shrinkage strain during the first 24 hour interval, which is similar to observations made for deeper targets inserted into Type B specimens in Part-I. Thus, if [$\varepsilon_{24}/\varepsilon_{48}$] is much less than 70%, then monitoring should be extended for a longer duration. This was the case for the C-0.55 and M-0.55 mixture specimens in which [$\varepsilon_{24}/\varepsilon_{48}$] ≈ [$\varepsilon_{48}/\varepsilon_{120}$]. If the duration of the monitoring is extended, in this study, up to 120 hours then we can compare the percentage of total shrinkage contributed by each subsequent 24 hour interval of shrinkage monitoring. For the C-0.55 mixture specimen, the shrinkage strains monitored during the subsequent consecutive 24 hour intervals after 48 hours of monitoring registered progressively smaller ratios. As can be seen in Fig. 5, it seemed to take120 hoursfor the water of the C-0.55 mixture specimen to evaporate, which isconfirmed by the smallest ratios registered by the shrinkage monitoredbetween 96 to 120 hours of monitoring. It should be noted that the ratio of the shrinkage strain registered by the C-0.45 mixture specimen during the first 24 hours,[$\varepsilon_{24}/\varepsilon_{48}$] is similar to that of the shrinkage strain registered by the C-0.55 mixture specimen up to 48 hours after adding water to the mix when the total shrinkage strain taken into consideration is that registered up to 120 hours, [$\varepsilon_{48}/\varepsilon_{120}$].



(a) (b)



(c)

Fig. 4 Ratios of S-1 (a), S-2 (b) and S-3 (c) shrinkage strains developed in Type C specimens between consecutive 24-hour intervals up to 120 hours of monitoring for OPC mixtures under "sealed" condition

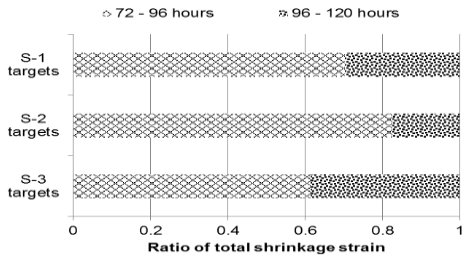


Fig. 5 Ratios of shrinkage strains monitored between 72 to 96 hours and 96 to 120 hours for S-1 to S-3 targets in C-0.55 mixture specimen

IV. CONCLUSIONS

For OPC mixtures, depending on the w/c ratio of the mixtures, it was found that there existed an "optimum" w/c ratio in which micro-cracks at a vertical interface can be reduced or eliminated. It was also found that the early age shrinkage is significantly affected by the size of specimen.The adverse effects of early age shrinkage followed by subsequent drying shrinkage could extend for more than 48 hours after adding water to the mix. The shrinkage that developlater, up to 120 hours, could be attributed to prolonged moisture loss and temperature development especially for the mixtures with a higher w/c ratio of 0.55. The effects of the early age and subsequent drying shrinkage owing to prolonged moisture loss should be classified as part of early age shrinkage even if this occurs beyond 24 hours after adding water to the mixture on account of the size effect for specimens cast with cementitious mixtures with higher w/c ratios.

As the size of the composite specimens becomes larger (Type C specimens) the effects of both prolonged temperature rise and prolonged moisture loss duration must be taken into consideration in order to minimize the potential for cracking. The experimental study has shown that material selection considering the temperature rise and moisture loss of fresh concrete mixture provides a new perspective for ensuring minimized potential for cracking at vertical interfaces under the "sealed" condition. The presence of an embedded structural steel section within the composite specimen also has an impact, as the steel section is prone to expansion as the temperature rise before subsequently contracting as the temeprature reduces. Depending on when this occurs vis-à-vis shrinkage effects at the interface, the potential for cracking may also arise.

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