COMPARISON BETWEEN IN-SITU EXPANSION MEASUREMENTS ON AAR-AFFECTED BEAMS, DRILLED CORES AND LARGE SAWN SECTIONS

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Abstract

Commonly, residual expansion of concrete elements is measured on drilled cores, under storage conditions of 38 °C, 100% RH, which may not correlate with expansion of field concrete. This paper presents the results of expansion measurements made on AAR-affected, prestressed deck planks under field conditions, and on large sawn sections and core samples taken from the planks and stored at 38 °C, 100% RH.

The results showed that longitudinal expansion of planks was small, as expected, whereas transverse expansion was large and variable in different locations on the planks. The cores and sawn sections showed different expansion levels depending on their AAR status. The plank with the worst cracking expanded more expansion of concrete.than the cores, whereas the other planks, and section cut from them, exhibited only 50% of the corresponding core expansion, i.e., core expansion may overestimate the confinement stress needed for restraining field

Keywords: Concrete**;** Prestressed-plank; AAR; Core-Expansion; In-situ-Expansion

1 INTRODUCTION

The deck of a six-span bridge structure, built in 1989, consists of precast, prestressed planks, with 16 planks per span. The planks were reported to have been damaged by AAR [1, 2]. Figure 1 shows the plank geometry and details of reinforcement and prestressing cables. The planks measured 11.8 x 0.6 x 0.38m. The soffit of the planks exhibited parallel longitudinal cracking (Figure 2), which was previously attributed to alkali-aggregate reaction (AAR) [1, 2].

Original drawings of the planks specified minimum 28-day compressive strength of 40 MPa, and transfer strength of 35 MPa. The calculated hog of 40 mm at 28 days was based on the following assumptions that had been made at the time of construction: density = 2600 kg/m3; elastic modulus at transfer = 36.7 GPa; steam curing at 70°C for 8 hours; plank self weight = 6.5 tonnes; storage after steam curing in open air at 20°C average temperature, and RH of 50-75%. References cited above include the results of durability tests and strength assessment of the concrete.

Determination of strength properties of cores taken earlier from other AAR-affected planks [1] indicated that the compressive strength and elastic modulus were reduced by as much as 30% and 50%, respectively. Mechanical properties of concrete are known to deteriorate due to AAR [3, 4]. The extensive reaction and significant reductions in the strength properties of the pre-stressed planks was of concern in relation to their load-bearing capacity, as excessive expansion could cause loss of prestress and bond failure resulting in sudden collapse under load. The deck was replaced in 2003, and the AAR-affected planks stored at the bridge site.

In practice, the residual expansion of AAR-affected concrete elements is assessed by drilling core samples out of the elements and determining their expansion potential. The core expansion may not represent that of the whole element. The discarded planks provided an opportunity to compare the residual expansion of the planks under field conditions, with those of core samples and slices cut from them under laboratory conditions. This paper compares the magnitude of residual expansion measured on the various samples, to clarify whether core expansion can represent the residual expansion of the whole element in the design of rehabilitation strategy.

2 EXPERIMENTAL WORK

Three planks of varying degrees of cracking were selected by the bridge owners for investigation, and labelled least cracked, intermediate and worst, based on their interpretation of the extent of cracking (Table 1). Figure 3 shows cracking in two of the planks. Eleven cores of 95 mm diameter were taken through the thickness of the whole plank (380 mm) from each of the three planks for various tests, including petrographic examination, scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis, residual alkali content and cement content of concrete, compressive strength, splitting tensile strength, elastic modulus, as well as residual expansion (38°C, 100% RH) and maximum expansion potential (38°C, in 1M NaOH).

Intact segments of the full cross sectional area, taken from one end of the planks, were cut as blocks measuring 600 x 380 x 300 mm, and fitted with Demec length measurement studs, which formed a grid of measurements (Figure 4) , and then moved to storage conditions of 38°C, 100% RH, for accelerated exposure and expansion measurement. In addition, the coarse aggregate used in the planks was separated by crushing about 50 kg portions of each of two planks and tested by accelerated mortar bar test (AMBT) and concrete prism test (CPT) in accordance with RTA T363 and RTA T364 methods, respectively.

The three planks were stored outdoors and exposed to natural exposure conditions. They were fitted with a square grid of 3x3 measuring points, which were installed on the surface of the planks by drilling holes at 200mm centres, and gluing in 15mm long stainless steel screws, which had an appropriate dimple on the exposed surface for locating the pin of the Demec Gauge measuring arms. The grid allowed concrete expansion to be measured in both longitudinal and transverse directions. A moisture- and alkali-resistant epoxy resin was used for fixing the screws into the concrete. Figure 5 represents the measurement grid on the smooth surface of the three planks, which was forming the bridge deck soffit when they were in service.

3 RESULTS

Details of all the test results have been presented elsewhere [1], and only a summary is given here. Measurements of the residual expansion have continued since then and are updated in this paper.

3.1 Visual Observations

The soffit of all the planks showed distinct parallel longitudinal cracking as shown in Figure 3. More cracking existed on the side faces of planks M 26 and M 67 than in M 12. Core holes drilled from each plank showed that the longitudinal cracks penetrated to the depth of the prestressing cables. This was more evident on the slices of concrete cut off for expansion measurement. These cracks appeared to run parallel to the soffit, i.e., perpendicular to the direction of coring, and were seen as the delamination plane on cores. In cores from M 12 and M 26 only some of the drilled cores showed delamination at prestressing cables, whereas in Plank 67 all cores exhibited delamination.

Much more internal cracking was seen in the aggregate particles of plank M 67 than M 12; Plank 26 being intermediate. The internal cracking of aggregate particles is related to the extent of AAR-induced expansion in the concrete. The fissile nature of the meta-sedimentary rock in Plank M 67 would have contributed to this feature, even if the extent of AAR were the same. It was noted that AAR rimming was rather weak in Plank M 12, strong in Plank M 67 (which contained the fissile aggregate), and moderate to strong in Plank M 26 [1]. The percentages of visibly reacted aggregate particles were determined to be 7%, 70% and 31% for planks M 12, M 67 and M 26, respectively.

3.2 Petrographic observations on cores

The coarse aggregate phase was the same in planks M12 and M26; being a porphyritic acid igneous rock resembling dacite/latite. In plank M67, the majority of coarse aggregate particles were of greywacke rock type, in which the grain size and distribution of minerals varied considerably. In most particles, a fine matrix of quartz and mica surrounded coarse quartz and feldspar particles. The micaceous matrix showed definite lamination/orientation features, indicating the fissile nature of the rock. Mildly to strongly strained quartz was considered to be the reactive component of both aggregate types.

Plank M26 and M67 showed significant microcracking in the cementitious matrix, and in some zones several branching and parallel microcracks were present. Considerable carbonation was noted along the length of these cracks, indicating that they were old cracks. These were also wider than the other microcracks in the matrix. Overall, the petrographic examination clearly demonstrated the presence of AAR in all the planks.

3.3 SEM /EDX Examination

Extensive observations were made on the morphological features and chemical composition of the secondary reaction products found in concrete specimens taken from the planks.

Plank M 12, showed extensive formation of AAR products, as well as mild delayed ettringite formation (DEF). The EDX spectra generally indicated that the concrete alkali content was probably high and crystals with the composition of sodium hydroxide were observed in some locations. The cement paste near reacted aggregate particles appeared to be impregnated with AAR gel,

AAR products were more extensive in Plank M 67 than in plank M 12. The alkali content of the cement was also very high, but instead of NaOH crystals fibrous crystals of sodium carbonate had formed in the paste. This plank exhibited stronger DEF, which indicated that this plank may have been subjected to a significantly higher curing temperature. The combination of strong AAR and DEF was probably the reason for the more advanced stage of cracking and deterioration in Plank M 67, although the bridge owners labelled M26 as worst cracked.

The extents of both AAR and DEF were similarly large in Plank M 26, despite the fact that much fewer aggregate particles exhibited the visual effects of AAR rimming.

It appears that the difference in the extent of damage to the planks could be related to the curing temperature effect (magnitude and duration). In the more extensively damaged planks, gel-filled cracks at the aggregate-paste boundaries were around 200 μm in width (usually 20 μm for ettringite bands). Compared to the aggregate size of 20 mm, this represents a free expansion of 1% or 10,000 μstrain. Although the longitudinal expansion of the planks is suppressed by the prestressing cables, expansion does occur in the transverse direction.

3.4 Cement content and residual alkali content of concrete

Representative portions of the planks were pulverised and their cement content as well as water soluble alkali contents determined. The results are given in Table 2. The cement content was estimated from the acid soluble Ca, assuming that the CaO content of the cement is 63% by mass, and that the aggregate phases did not contain acid-soluble Ca. The cement appeared to be high in alkali, as seen from SEM/EDX data (see later).

The cement contents are high, which is common practice for precast, prestressed structural elements. Part of the differences among the planks could be related to sampling variation and the amount of aggregate component present in the sample. It could probably be said that the cement content of the planks was around 500 kg/m3.

The residual soluble alkali content of the planks is also high, considering that significant reaction has already occurred in the planks. This indicates that the planks would still undergo further AAR expansion.

3.5 Concrete Strength, elastic modulus and Porosity (VPV)

The middle sections, i.e., crack-free portions, of five cores from each plank, were cut to about 190 mm length for testing. Three segments were tested for compressive strength and two for splitting tensile strength. Two similar cores were used for determining the elastic modulus. Four slices of 50 mm thick were cut from one core from each plank and used for volume of permeable voids (VPV). The results are presented in Table 3, and show that plank M 12 had the highest strength, followed by Plank M 26 (visually most damaged) and Plank M 67 (intermediate). It should be noted that Plank M 67 contained the fissile aggregate, which could have lowered the strength. Nevertheless, it has been shown that most strength properties of AAR-affected concrete deteriorate compared to those of sound concrete [3-7].

The strength values given above may exaggerate the strength of the planks, as the soundest parts of the cores were tested. In fact, cores from Plank M 26, the worst damaged plank, showed significant variability in strength. Nevertheless, the strength values appear to be high, except for Plank M 67.

The splitting tensile strength of cores did not follow the trend of the compressive strength, and Plank M 26 and M 12 had the same strength values. This could have been due to variation and crack orientation in relation to loading direction. The compressive strength data are considered to be more reliable.

The VPV results are important in relation to transport mechanisms inside the concrete. Vic Roads specification section 610, clause 610.06, requires the VPV of test cores at the age of 28 days not to exceed 14% for the highest strength grade listed (55 MPa). The VPV values do not follow the visual damage ranking of the planks. This probably arose from the fact that VPV is measured on slices of cores 50 mm thick, and the selected portion may have included variable extents of microcracking.

3.6 Residual Expansion potential of Coarse Aggregate separated from Planks

As indicated earlier, the aggregate type was the same for Planks M 12 and M 26. Therefore, the aggregate components of planks M 12 and M67 were separated by crushing a large amount of concrete from each plank and hand picking the aggregate. The results of testing the recovered aggregates according to the AMBT (RTA T363 method) and CPT (RTA T364 method- similar to ASTM C-1293) are given in Table 4, and show that the residual reactivity of the aggregates is still high, i.e., they still contain reactive components that could further react. Given that sufficient residual alkali is also available, the planks are expected to continue to expand in the future.

3.7 Residual Expansion of Concrete Measured on Cores

Figure 6 shows the expansion curves for cores taken from the three planks and stored at 38°C, 100% RH and in 1M NaOH at 38°C. The core expansion represents the unrestrained, free expansion potential of the concrete. Data presented in Figure 6 clearly indicate the much larger residual expansion (38°C, 100% RH) of planks M12 and M67 compared to that of M26. This is attributed to the fact that M26 has already exhibited more extensive reaction and cracking to-date, leaving less potential for further reaction. Plank M 12 exhibited the largest residual expansion, as it has exhibited the least amount of reaction to date, i.e., it has more potential for further expansion.

This free expansion potential is suppressed by the prestressing cables and reinforcement bars in the planks, and only a proportion of it would be realised in the full planks. It is well known that steel reinforcement and applied stress have restraining effects on AAR expansion; the effects increasing with increased levels of reinforcement and applied stress [8]. It has been stated [9] that the field structure may only achieve around 50 % of the residual expansion of cores measured in the laboratory, due to differences in the two environments and because of the confinement experienced by the structure compared to the freely expanding cores under laboratory conditions. However, at low levels of steel reinforcement, the AAR expansion could result in yielding failure of mild steel [10].

Core expansion in 1M NaOH, 38°C occurred at faster rates and continued over the period of testing, which indicates that still large amounts of reactive components are present in the concrete and can react with the freely available alkali from the NaOH solution. Again, cores from Plank M26 showed the least expansion, which indicates that either lesser amounts of reactive components are left in the concrete (due to larger extent of initial reaction), or that the any new reaction products filled the existing cracks in the concrete, reducing the expansion potential.

Data in Figure 6, together with the fact that the residual alkali content of concrete is high, suggest that further expansion and cracking could be expected for the planks.

3.8 Expansion of Blocks Cut from the Planks (38°C and 100% RH)

Expansion measurements on the sawn blocks were conducted based on the grid shown in Figure 4. The results are presented as concrete expansion curves for the different grid locations in Figure 7 for blocks from Planks M 12 and M67, and in Figure 8 for the block from Plank M26.

The results in Figure 7 show that expansion in the longitudinal direction is rather low, being an average of around 0.03%. However, expansion in the transverse direction in the period of testing ranged from 0.10% to 0.40% for Plank M 12 and 0.06% to 0.15 % for Plank M 67, respectively. The results indicate that the steel components are restraining the expansion in the sawn blocks. These expansion values are considered deleterious, and could cause further cracking or crack widening.

The block cut from Plank M26 behaved quite differently, and transverse expansion was no longer larger than the longitudinal expansion. In fact, longitudinal expansion for most locations was larger than the transverse expansion. The reason for this observation is that Plank M26 was tested in flexure to failure, prior to the block being sawn off. This shows that the prestress was lost as a result of excessive flexure, and the sawn block no longer acted as a longitudinally restrained element.

Figure 8 shows that the block slightly shrank, rather than expand, in the transverse direction, and that the expansion in the longitudinal direction was rather small, with a maximum value of around 0.03%. This may have arisen because the flexure testing, and loss of prestress in the block, had generated sufficient space to accommodate the newly formed AAR gel (which would mitigate the expansion).

3.9 Residual Expansion of Planks Exposed to Outdoor Exposure Conditions

Unlike the core samples and the sawn blocks, which were stored under storage conditions of high temperature and humidity, the planks were kept outdoors. The measurement grid (Figure 5) allowed concrete expansion to be measured in both longitudinal and transverse directions.

The results obtained for Plank M 26 are presented in Figure 9, and the other planks showed very similar patterns for different directions of planks (not included due to shortage of space). As expected, the planks showed much less longitudinal expansion (eg. A1-A2 ; A2-A3) than transverse expansion (eg. A3-B3 ; B3-C3). There was even minor longitudinal shrinkage due to surface drying of the concrete. However, measurements in the transverse direction indicated that significant expansion is taking place across the planks.

The transverse expansion measured at 1200 days on the different points on Plank M 12 ranged from 0.17% to 0.33%. The corresponding range for Plank M 67 was 0.11% to 0.22% and for Plank M26 (1100 days) 0.19% to 0.42% (Figure 9). The cracking has significantly worsened in all the planks since the start of the measurements. Existing cracks have widened and new cracks have developed in the planks.

Data for other planks compared to that in Figure 9 show that, under outdoor exposure, Plank M67 exhibited lower expansion than other planks, probably due to the presence of internal aggregate cracking, which can accommodate some of the newly formed AR gel.

Unlike the situation with the sawn block from Plank M26, where the prestressing had been lost, Plank M26 itself maintained its prestressing because the longitudinal expansion was far smaller than the transverse expansion. Plank M26 showed the largest transverse expansion amongst the three planks, and also exhibited up to 0.05% longitudinal expansion, whereas the other two planks recorded longitudinal shrinkage. This is believed to arise because Plank M26 was previously used for a test which involved stripping away the concrete from portions of several prestressing cables to determine their stress level, as shown in Figure 10, which also shows a portion of the plank cross section where retraction of the cables is evident. This reduced the level of prestress in the plank, and enabled larger expansion in the plank.

The large expansion values obtained for all the planks indicate further deleterious expansion in the future, which will increase with time and probably cause new cracking and widening of existing cracks. This may reduce the bond strength of the prestressing cables and their load capacity.

3.10 Comparison of expansion measurements

Figure 11 compares the values of expansion recorded at the end of measuring period for each test. In the case of prestressed elements, longitudinal expansion in the direction of prestressing can be ignored, whereas transverse expansion is the main factor affecting the performance of the element. This also applies to the blocks cut from the planks. As Plank M26 had been loaded to failure prior to the expansion tests, the expansion results obtained subsequently may not relate to the condition of the intact element, so data on this plank is not used for comparing test data.

Amongst the tests performed on Plank M12 and M67, the core expansion in 1 M NaOH, 38 °C was the most severe, followed by core expansion at 38 °C, 100% RH. Both tests exaggerated the expansion potential of the plank, whereas expansion of blocks was closer to those of the planks. However, it is not practical to cut off blocks from in-situ elements, but taking and testing core samples is more feasible. Figure 11 indicates that in the case of this work, the expansion of planks under field exposure conditions was around 40% of core expansion at 38 °C, 100% RH. This is in agreement with conclusion of other studies [9] which stated that the field structure may only achieve around 50 % of the residual expansion of cores measured in the laboratory. If this relationship is applicable to other AAR-affected elements, then the level of restraint required to confine the AAR expansion may be overestimated if it is calculated based on the core expansion, as distinct from in-situ measurements.

4 SUMMARY AND CONCLUSIONS

Three precast, prestressed bridge deck planks which have suffered considerable but varying degrees of AAR were subjected to extensive investigations. The planks were fitted with a grid of Demec measuring studs and their expansion recorded over 1100-1200 days under outdoor exposure conditions. Core samples taken from the planks were subjected to laboratory expansion tests under two storage conditions of 38 °C, 100% RH and 1M NaOH solution at 38 °C. Blocks separated from the planks were also subjected to 38 °C, 100% RH, and their expansion monitored.

Results show that core expansion in the laboratory exaggerated the expansion which can be achieved by the host element under field conditions. The magnitude of expansion appeared to be inversely related to the level of prestress in the element.

Core expansion in 1M NaOH at 38 °C far exceeded that of the field concrete. However, core expansion at 38 °C, 100% RH, appears to be a useful predictor of concrete expansion under field exposure. The planks, which were stored outdoors, achieved about 40% of core expansion at 38 °C, 100% RH, which is in agreement with the published data.

REFERENCES

[1] Shayan, A, and Morris, H. (2002). Cracking in precast, prestressed deck planks in two bridges and rehabilitation options. ACI Materials Journal, Vol 99, March – April 2002, pp. 165- 172.

[2] Shayan, A., Al-Mahaidi, R. and Xu, A. (2008). Durability and strength assessment of AAR- affected Bridge deck planks. Proceedings of the 13th IAARC, Trondheim, Norway, 16-20 June 2008, 11 pp. 422-432

[3] Swamy, R.N. (1995). Effects of AAR on material stability and structural integrity. Proc. CANMET/ACI International Workshop on AAR in Concrete, Dartmouth, Nova Scotia, pp. 293-310.

[4] Shayan, A., Xu, A. and Andrews-Phaedonos, F. (2003). Development of a Performance Measure for Durability of Concrete Bridges. Proceedings of the 21st Biennial Conf, Concrete Institute of Australia, "Concrete in the third millennium", Vol 2, Brisbane, Australia, pp739-757.

[5] Ono, K. (1989). Assessment and repair of damaged concrete structures. Proceedings 8th International AAR Conference, Kyoto, Japan, pp. 647-658.

[6] Koyanagi, W., Rokugo, K. and Uchida, Y. (1992). Mechanical properties of concrete deteriorated by alkali aggregate reaction under various reinforcement ratios. Proceedings 9th International AAR Conference, London, U.K., PP. 556-563.

[7] Takemura, K., Ichitsubo, M., Tazawa, E. and YonekurA, A. (1996). Mechanical performance of ASR affected nearly full-scale reinforced concrete columns. Proceedings 10th International AAR Conference, Melbourne, Australia, pp. 410-417.

[8] Hobbs, D.W., (1988). Alkali silica reaction in concrete, Thomas Telford, London

[9] Tomita, M., Miyagawa, T. and Nakano, K. (1989). Basic study for diagnosis of concrete affected by ASR using drilled concrete cores. Proceedings 8th International AAR Conference, Kyoto, Japan, pp. 779-784.

[10] Fujii, M., Kobayashi, K., Kojima, T. and Maehara, H. (1987). The static and dynamic behaviour of reinforced concrete beams with cracking due to alkali-silica reaction, in concrete alkali aggregate reaction (P.E. Grattan-Bellew, editor), Noyes publications, N.J., USA, pp. 126-130.

Table 1: List of the three planks tested

Plank ID	Laboratory designation	Visual † cracking
M 12	C07/ 1532	Least
M 67	C07/ 1533	intermediate
M 26	C07/ 1664	Worst

† At the time of delivery (rated by bridge owners)

Table 2: Cement content and water soluble alkali content of dry concrete (kg/m³)

Plank ID	Cement content	Na_2O	K_2O	Na_2O_{eq}†
M 12	475	1.79	1.25	2.61
M 67	533	2.41	1.47	3.38
M 26- surface	-	2.41	1.51	3.41
M 26- interior	563	2.11	1.36	3.00
† $Na_2O_{eq} = Na_2O + 0.658\ K_2O$				

Table 3: Strength and VPV of the concrete cores extracted from the deck units

Plank ID	Compressive strength (MPa)	Splitting Tensile Strength (MPa)	elastic modulus(GPa)	VPV (%)
M 12	76.7 ± 2.7	5.3	28.4	12.6
M 67	39.2 ± 8.6	5.4	15.4	12.8
M 26	60.3 ± 10	4.9	26.5	15.4

Table 4- Results of AMBT and CPT tests on the two aggregates separated from two planks

Plank ID	AMBT Expansion (%)		CPT Expansion (%)	Classification
	10 days	21 days	1 Year	
M12	0.20	0.40	0.28	Reactive
M67	0.16	0.35	0.23	Reactive

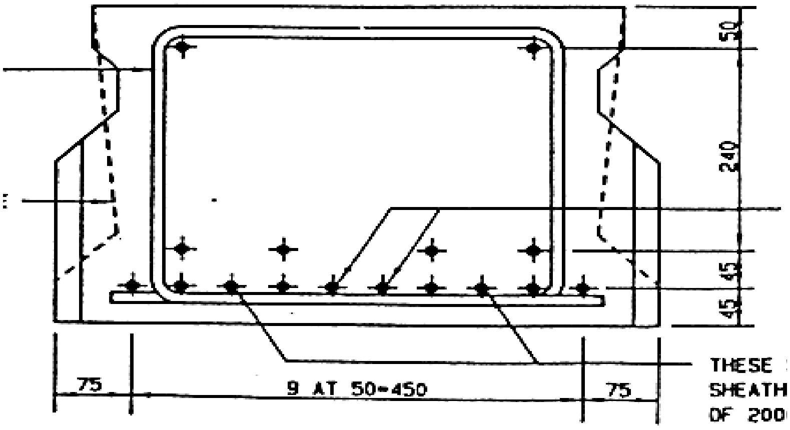


Figure 1- Details of steel reinforcement and prestressing cables in the planks

Figure 2- Longitudinal parallel cracking in the soffit of deck planks

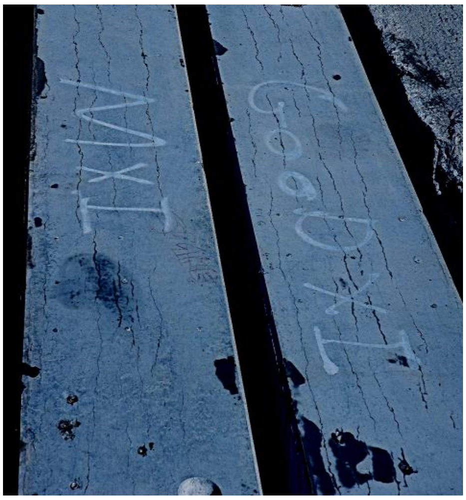


Figure 3- cracking in the soffit of planks M67 (left) and M 12 (right) highlighted by wetting

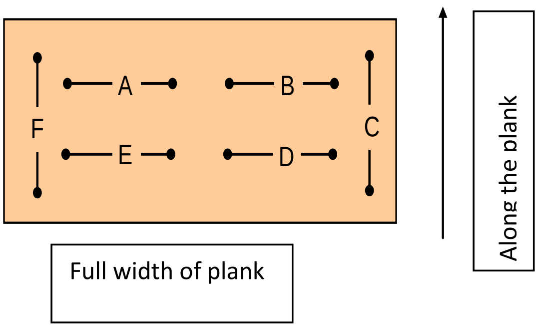


Figure 4- Measurement grid on Blocks cut from the planks (300 x 600 x 380 mm) for expansion measurement at 38°C, 100% RH, in transverse (A, B, D, E) and longitudinal (C, F) directions

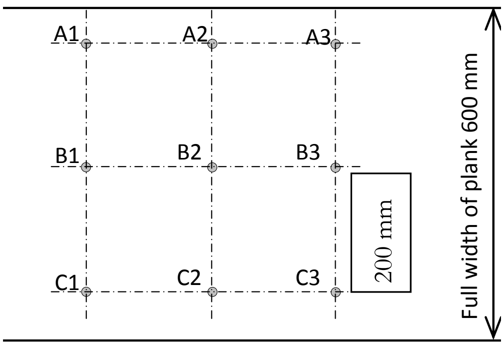
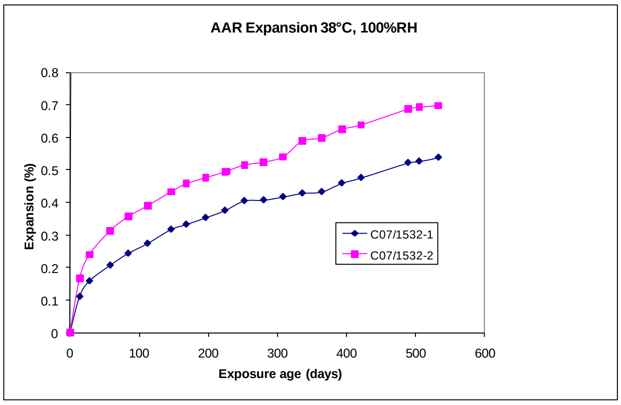
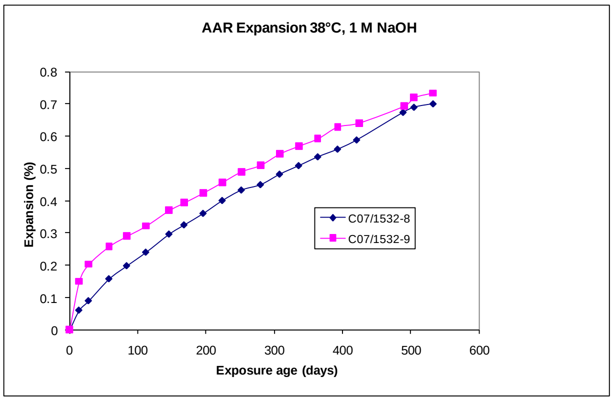


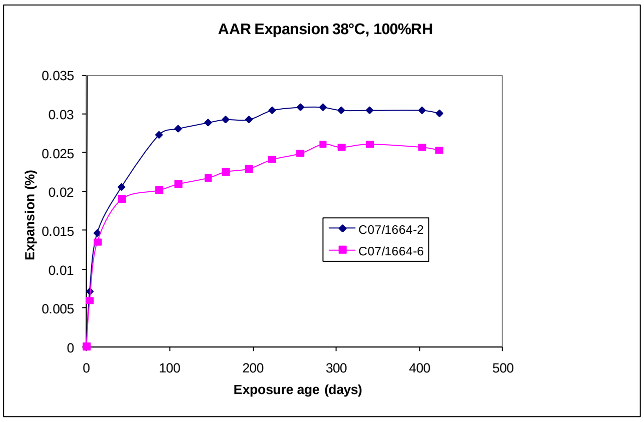
Figure 5- Square grid of expansion measurement points on plank surfaces



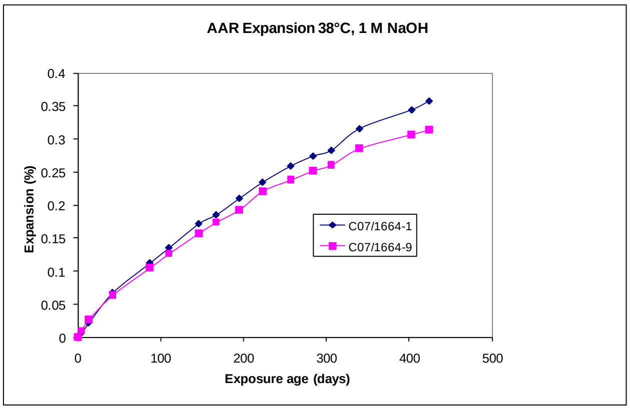
Plank M12



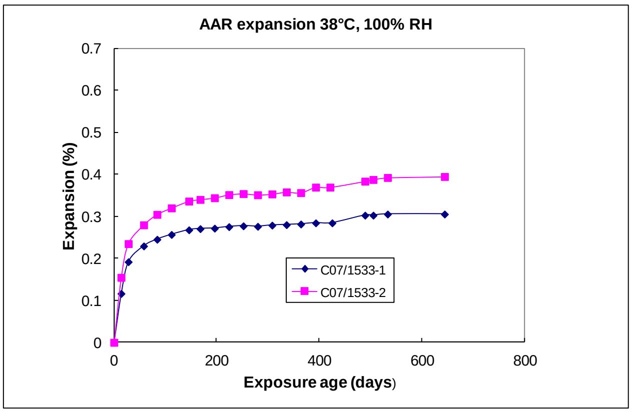
Plank M12



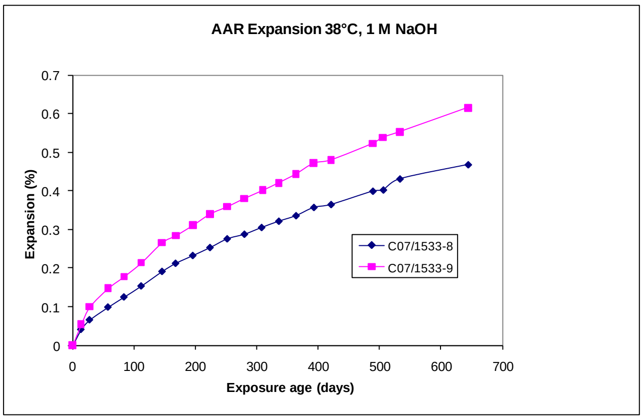
Plank M26



Plank M26



Plank M67



Plank M67

Figure 6- Expansion curves for cores taken from the various planks under the storage conditions indicated

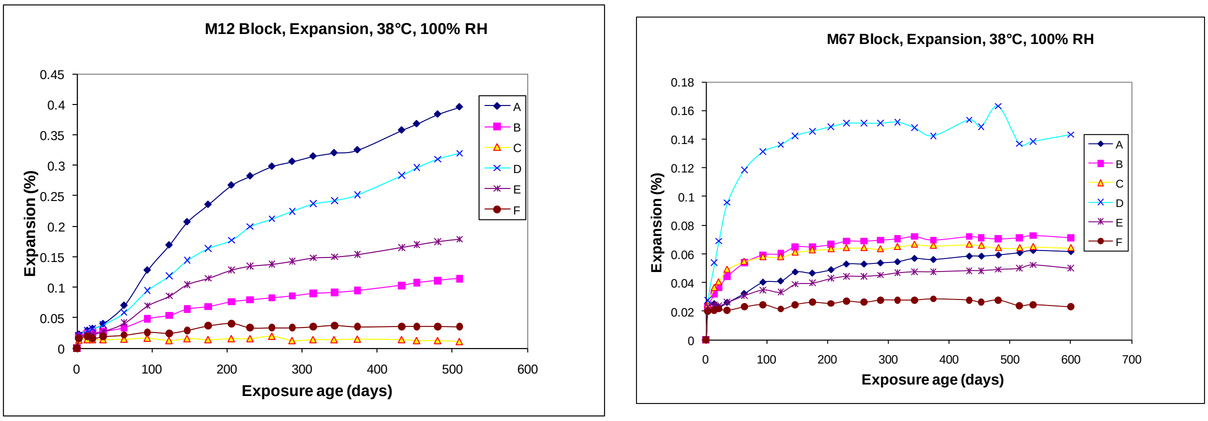


Figure 7- Expansion measured on the surface of sawn Blocks M12 and M67 in the transverse directions A, B,D and E, as well as longitudinally in the direction of the prestress (C and F)

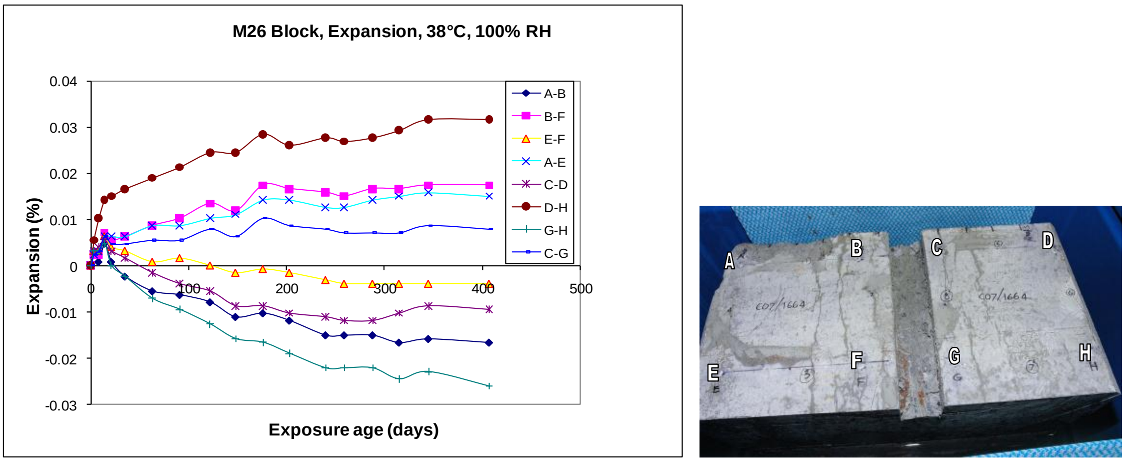


Figure 8- Expansion measured on the surface of sawn Block M26 in the transverse directions A-B, C-D, E-F and G-H, as well as longitudinally in the direction of the prestress D-H, C-G, B-F and A-E

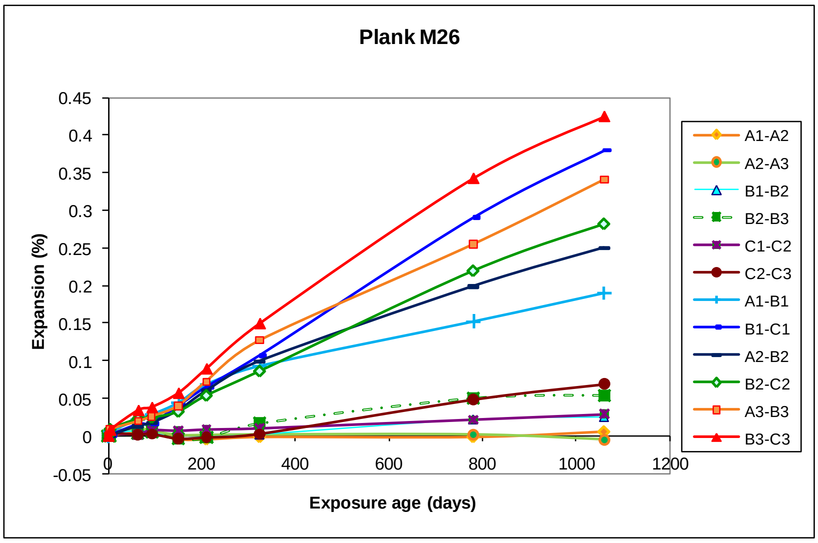


Figure 9- Expansion measurements on planks under outdoor exposure conditions. Locations for A1-A2, A2-A3, B1-B2, B2-B3, C1-C2, C2-C3 are along the planks, whereas A1-B1, B1-C1, A2-B2, B2-C2, A3-B3 and B3-C3 are in the transverse direction, and perpendicular to the existing parallel cracks.

Figure 10- Left: Plank M26 after testing. The expansion measurements grid is on the far left. Right: retraction of prestressing cables (prestress loss) over the period of testing

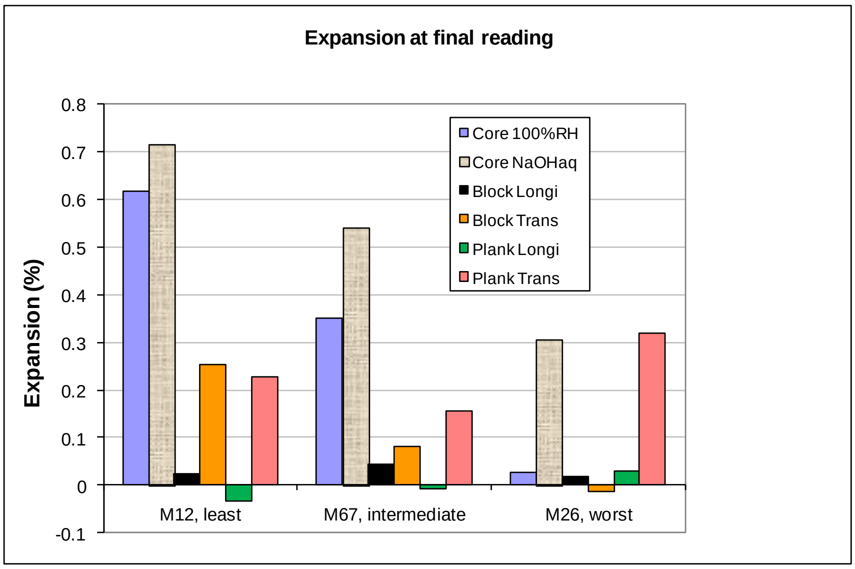


Figure 11- Comparison of expansion measured on planks and different specimens at the end of the testing periods for the test concerned