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Published in:
Proceedings of fib Symposium 2015

Publication date:
2015

Document Version
Peer reviewed version

HOMOGENEITY AND STRENGTH OF MORTAR JOINTS IN PEARL-CHAIN BRIDGES

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Abstract

The load carrying mortar joints in Pearl-Chain Bridges are cast vertically which means that they have a placing depth of up to 2.40 m. In the present paper, the feasibility of casting 2.40 m high homogeneous vertical mortar joints is examined. Three high-strength, expansive, self-compacting, ready-to-mix mortar products are tested. To the authors' knowledge, no previous published work has documented the homogeneity and properties of mortar joints of such a height. Hence, the present study documents a practical test procedure where the homogeneity of three mortar joints measuring 20 x 220 x 2400 mm has been tested and compared by measuring compressive strength, variation in rebound value, variation in density, and separation. In addition, the appearance of the surface texture has been visually assessed. The measurements indicate that, for all three mortars tested, it is possible to cast homogeneous 2.40 m high mortar joints. Moreover, the strength of the three mortars meets the requirements for the Pearl-Chain Bridge application. However, when inspected two of the mortars had many surface air bubbles which is a serious concern regarding durability of the mortar joints.

Keywords: Bridge Engineering, Homogeneity, Materials, Mortar Joints, Pearl-Chain Bridges

1 Introduction

Pearl-Chain Bridge Technology introduces an innovative arch bridge solution that challenges the traditional way of constructing highway bridges. The substructure of a Pearl-Chain Bridge is made of prefabricated Super-Light Deck Elements (SL-Deck Elements) consisting of light-aggregate concrete and normal concrete (Hertz, Castberg & Christensen 2014; Hertz 2015). Each SL-Deck Element is 1.65 m long, 0.22 m thick, and up to 2.40 m wide, depending on the bridge design. Ducts are cast into the SL-Deck Elements in the longitudinal direction to enable post-tensioning. Because each SL-Deck Element is given a slight inclination at the ends, an arch shaped substructure is created by collecting and post-tensioning several SL-Deck Elements on a wire, like pearls on a string. To ease the assembly the substructure is placed on its side when constructed, see Fig. 1. However, this means that the mortar joints between the SL-Deck Elements are cast vertically, requiring placing depths of up to 2.40 m.

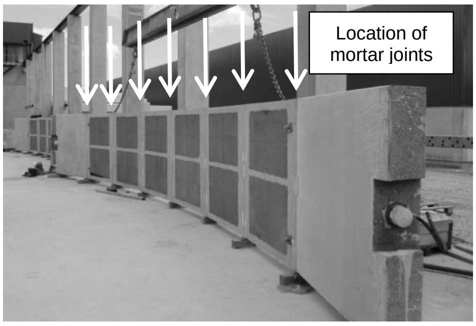

Fig. 1 Collecting and post-tensioning several SL-Deck Elements to create an arch substructure. The mortar joints between the elements are 1.75 m high. The photo shows a test arch with a span length of 13 m.

Fig. 2 After casting the mortar joints and post-tensioning the Pearl-Chain Bridge arch substructure, it is placed in position by a crane. The photo shows a test arch with a span of 13 m and a width of 1.75 m. Several arches can be placed next to each other to provide the necessary width of the bridge.

When the SL-Deck Elements have been placed in position, self-compacting mortar joints are cast between the elements, after which the arch is post-tensioned. Subsequently, a crane is used to lift and rotate the arch and place it at the right location (Halding & al. 2015). This can be seen in Fig. 2. Depending on the total width of the bridge, several arches are placed next to each other.

The mortar joints are cast between the SL-Deck Elements in the bridge arch substructure to transfer the forces between the elements. These joints can be considered a weak link as far as the durability of the substructure is concerned. Self-compacting mortar products are typically applied in constructions that require joint thicknesses below 400 mm. In Pearl-Chain Bridges, a placing depth of up to 2.40 m is needed, which exceeds the thickness of typical fields of application of well-known mortar products. Therefore, the mechanical and moisture properties of mortar joints in Pearl-Chain Bridges need to be tested to determine their durability.

In the present paper, three commercialized high-strength, expansive, self-compacting mortar products are placed at 2.40 m and their homogeneity and strength are tested to find the most suitable candidate for mortar joints in Pearl-Chain Bridges. This paper describes the first step, namely the selection of a suitable mortar product for the mortar joints in Pearl-Chain Bridges. The second step, the comprehensive test of the chosen mortar product, is described in a journal paper to be published later this year.

2 Specimen preparation

2.1 Materials

A high-strength, expansive, self-compacting mortar product for Pearl-Chain Bridges is desired to provide sufficient strength, eliminate shrinkage problems and ease the casting procedure. Three such mortar products from three different producers were selected for the tests. All three mortar products were ready-to-mix products that only needed addition of water. Characteristic values of the mortars have been summarised in Table 1.

Table 1 Comparison of characteristic values of commercialized high-strength, expansive, self-compacting mortars which have been tested.

	Mortar A	**Mortar B***	**Mortar C**
Placing depth [mm]	20-150	No information	5-30
Pot life at 20ºC [min.]	10	20	90
w/c-ratio	-	0.31	0.35
Aggregate size [mm]	0-4	0-1	0-1
Water addition [kg] per 25 kg dry mortar	3.40	3.90	3.25
1 day compressive strength [MPa]	20	40	40
7 days compressive strength [MPa]	60	73	60
28 days compressive strength [MPa]	80	87	80
Expansion** [%]	0-2	1	0.5

**The values given for Mortar B are not characteristic values but declared typical values measured at 20ºC.*
***The approaches used when determining the expansion are not well defined. For Mortar A and Mortar C the data sheet does not declare how the parameter is found. For Mortar B it is stated that the expansion is based on the volume expansion of a rubber glove that is filled with mortar and weighed above and below water before and after hardening.*

2.2 Casting of mortar joints

The dimensions of the mortar joints in Pearl-Chain Bridges are 20 x 220 x 2400 mm. A 2400 mm high mortar joint is an upper limit of the joint height in any possible design of the bridge construction, and therefore this is tested in the present study. The first step in the selection of the most adequate mortar product was to construct a formwork with the same dimensions. To ensure sufficient stiffness of the formwork each mortar chamber was made by using a double layer of coated plywood with a thickness of 12 mm each. The three chambers are seen in Fig. 3.

To relate the tests to the most practical application in real life, it was tested how the mortars behaved when cast from the top of the formwork, i.e. when pouring the mortars from above by use of a funnel, such that the mortars had a placing depth of 2400 mm. This is shown in Fig. 4.

Fig. 3 Test setup with three wood chambers, each with a dimension of 20 x 220 x 2400 mm. The 40 l compulsory mixers used to mix the mortars are also seen.

Fig. 4 The mortar was cast by pouring the mixed mortars through a funnel placed on top of the formwork. Hereby, the mortar had a placing depth of 2400 mm.

The mortars were mixed in a 40 l compulsory mixer. For each mortar product 50 kg mortar was mixed for 5 min. with the water amount given in Table 1. After 2:30 min. the blades were cleaned for lumps of mortar powder. Afterwards the mortar was mixed for additionally 2:30 min.

Subsequently, the mortars were poured into the formwork and allowed to harden in the formwork for 7 days. Moreover, nine mortar prisms with dimensions of 40 x 40 x 160 mm were cast for each mortar product to investigate the compressive strength.

3 Experimental procedures

Besides from a visual assessment of the three mortar joints, several tests were carried out with the purpose of revealing any inhomogeneity and potential separation of the mortars.

3.1 Compressive strength test setup

The compressive strength of the mortars was determined in accordance with EN 196-1 on a 300 kN MAN compressive test machine. The prisms tested measured 40 x 40 x 80 mm and were cut from the cast prisms, cf. EN 196-1. The compressive strength, f_c, was determined after 1 day, after 7 days and after 35 days from the expression

$$f_c = \frac{F_c}{A} \tag{1}$$

where F_c [N] equals the maximum load at failure, and A equals the compressed area = 1600 mm^2.

3.2 Schmidt hammer test setup

The Schmidt hammer was used to evaluate the homogeneity along the 2400 mm height of the mortars. The rebound value was measured for every 5 cm from the bottom to the top of the joints, after 1 day and after 7 days. The measurements were not taken at the same location after 1 day and after 7 days, but were shifted slightly to avoid influence from previous measurements. The rebound values were measured on the side of the joint, which had a width of 20 mm. The measurements were carried out when the mortar joint was still inside the formwork. This was possible by removing only the coated plywood covering the 20 mm side of the mortar joint.

3.3 Density test setup

The homogeneity of the mortar joints was also considered by determining any differences in density between the top section, the middle section and the bottom section of the mortar joints. Five prisms were cut from each joint specimen as shown in Fig. 5.

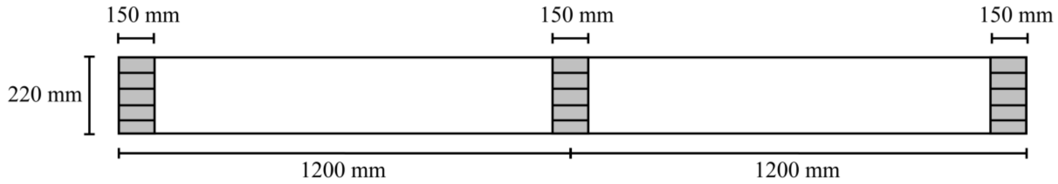

Fig. 5 Mortar joint rotated 90º compared to Fig. 3. The location of the prisms cut for measurements of density is highlighted.

The volume of the prisms was determined from the water displacement method based on Archimedes' principle. Hereby, the dry density, ρ_d, was determined as

$$\rho_d = \frac{m_d}{m_{ssd} - m_{sw}} \cdot \rho_w \quad (2)$$

where m_d [kg] is the dry mass of the specimen after drying until weight constant at 105ºC, m_{ssd} [kg] is the mass of the vacuum water saturated specimen in saturated surface dry condition, m_{sw} [kg] is the mass of the vacuum water saturated specimen submerged in water, and ρ_w [kg/m^3] is the density of water.

3.4 Bleeding test setup

Bleeding of the three mortar joints was determined in a slightly modified version of EN 480-4. According to EN 480-4 bleeding is determined from samples cast in 280±10 mm high cylindrical moulds. However, since the intention with the present tests is to consider inhomogeneity of 2400 mm high mortar, the procedure described in EN 480-4 was followed for the 2400 mm high specimens instead. According to EN 480-4 bleeding is determined by collecting surface water in a pipette during 10 min. intervals over the first 40 min. after casting, followed by measurements at 30 min. intervals until cessation of bleeding. The bleeding, B, can then be expressed as

$$B = \frac{m_w}{w \cdot m_s} \quad (3)$$

where m_w [kg] is the mass of bleed water, where m_s [kg] is the mass of the sample, and w is the proportion of water in the fresh mortar by mass in percent.

4 Results

The applied test methods have intended to determine the strength and homogeneity of three different mortar joints measuring 20 x 220 x 2400 mm.

4.1 Compressive strengths

The compressive strength determined after 1 day, 7 days and 35 days is shown in Fig. 6 together with the corresponding values from Table 1. Each measured value represents an average of six results. The compressive strength was measured after 35 days rather than after 28 days due to complications with the testing machine. However, it is expected that the strength development has stabilized so much after 28 days that the compressive strength determined after 35 days is in the same order of magnitude.

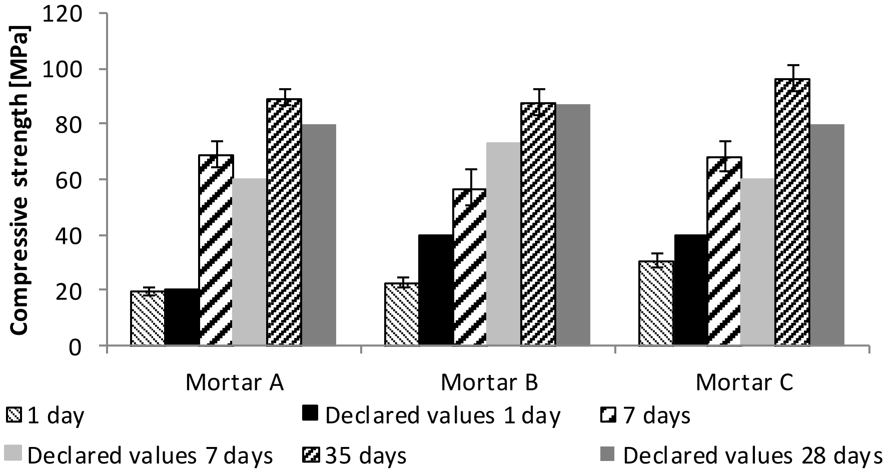

Fig. 6 1 day, 7 days and 35 days compressive strengths and standard deviations determined in accordance with EN 196-1 when Mortar A, Mortar B and Mortar C have been mixed in a compulsory mixer. Measured values and declared values are shown. The measured values are based on six specimens each.

As seen from Fig. 6 the declared 1 day compressive strengths are 77% and 29% higher than the measured values for Mortar B and Mortar C, respectively. After 7 days it is only the declared value of Mortar B which is still higher than the measured value, now being 28% higher. After 35 days all three mortars reach the declared values for 28 days. Mortar A and Mortar C have 12% and 21% higher measured compressive strengths than the declared values, respectively. Mortar C reaches the highest compressive strength of all three mortars with 97 MPa after 35 days. Even though Mortar A has the slowest strength development during the first 24 h it reaches 90 MPa after 35 days.

4.2 Schmidt hammer rebound values

The results from the Schmidt hammer tests are shown in Fig. 7. The variation in rebound value along the height of the mortar joints together with the average value are shown after 1 day and after 7 days.

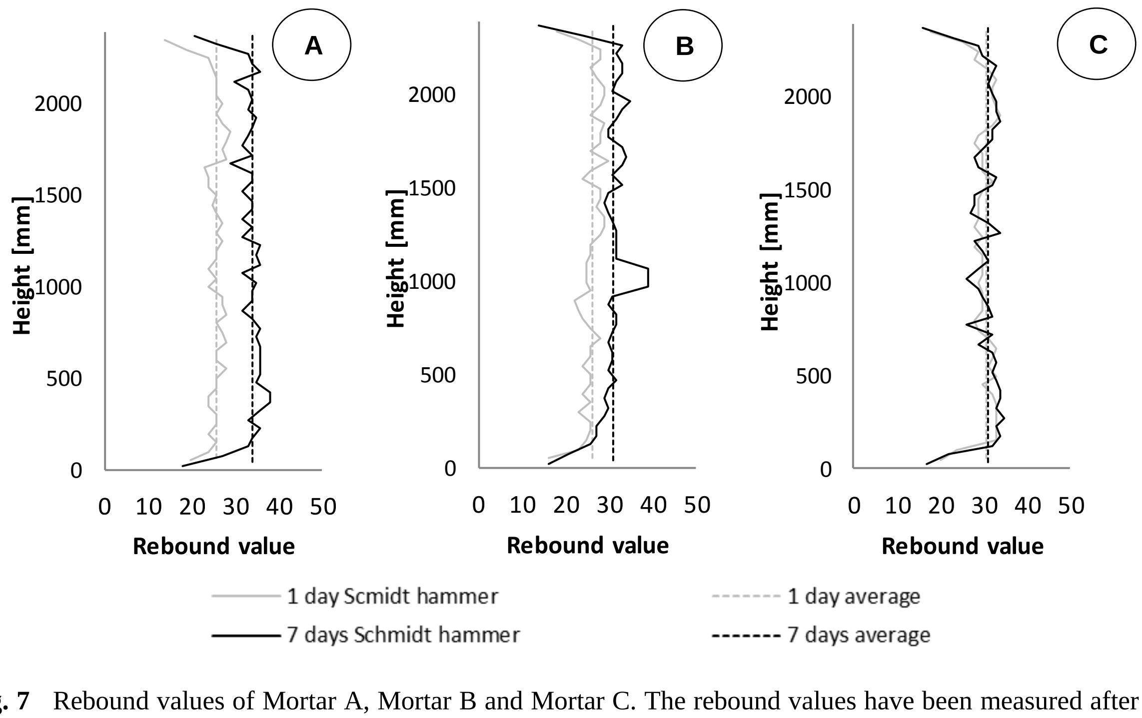

Fig. 7 Rebound values of Mortar A, Mortar B and Mortar C. The rebound values have been measured after 1 day and 7 days along the height of the mortar joint with a spacing of 5 cm between the measurement points. The rebound values are given without units.

The variation in rebound values in Fig. 7 does not intend to represent a development in strength but a variation in homogeneity. It can be seen that for all mortar joints there is a boundary effect influencing the measurement close to the top and at the bottom of the joints. This is expected to be caused by less mortar contributing to the rebound itself because the Schmidt hammer is placed close to the edge. In the calculation of the average value these boundary effects have not contributed.

For Mortar A, Fig. 7 shows that after 7 days there seems to be a slightly higher rebound value at the lower part of the joint (0-1200 mm) compared with the upper part of the joint (1200-2400 mm). For Mortar B the deviation around midpoint after 7 days is expected to be an error in two of the measurements. Apart from these, the rebound values are fairly constant for Mortar B. Also Mortar C seems to have slightly higher rebound values at the lower part of the joint than at the upper part. However, the overall picture is that a fairly constant rebound value is observed for all mortars after 1 day and after 7 days which is confirmed from Table 2. The table shows the average rebound values and the corresponding standard deviations for the three mortars after 1 day and 7 days. In the calculations the aforementioned incorrect points have not been considered.

Table 2 Average rebound values for Mortar A, Mortar B and Mortar C and the corresponding standard deviation after 1 day and after 7 days.

	Mortar A		**Mortar B**		**Mortar C**	
	1 day	*7 days*	*1 day*	*7 days*	*1 day*	*7 days*
Average	26.0	34.1	26.4	31.1	30.7	31.1
Std. dev.	1.4	1.9	1.9	1.9	1.8	2.3

4.3 Variation in density

The variation in dry density and standard deviation between the top, middle and bottom section for the three mortars is shown in Fig. 8.

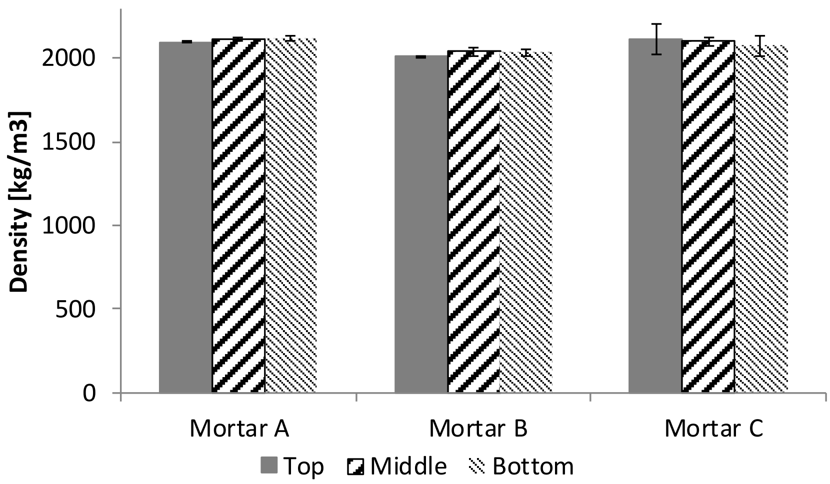

Fig. 8 Variation in dry density and standard deviation between top, middle and bottom section for the three mortars.

From Fig. 8 no significant variation for any of the mortars is observed between the top, middle and bottom sections. The average dry density for Mortar A, Mortar B and Mortar C is 2111 kg/m^3, 2028 kg/m^3 and 2098 kg/m^3, respectively.

4.3 Bleeding and separation

Bleeding was examined by looking for surface water in the first period after casting. No surface water was present in any of the three cases, indicating that no bleeding took place. This means that no separation occurred.

4.4 Visual appearance

The visual comparison of the three mortar products revealed severe differences in the appearance of the surface texture. Fig. 9 shows the surface texture of the three mortar joints.

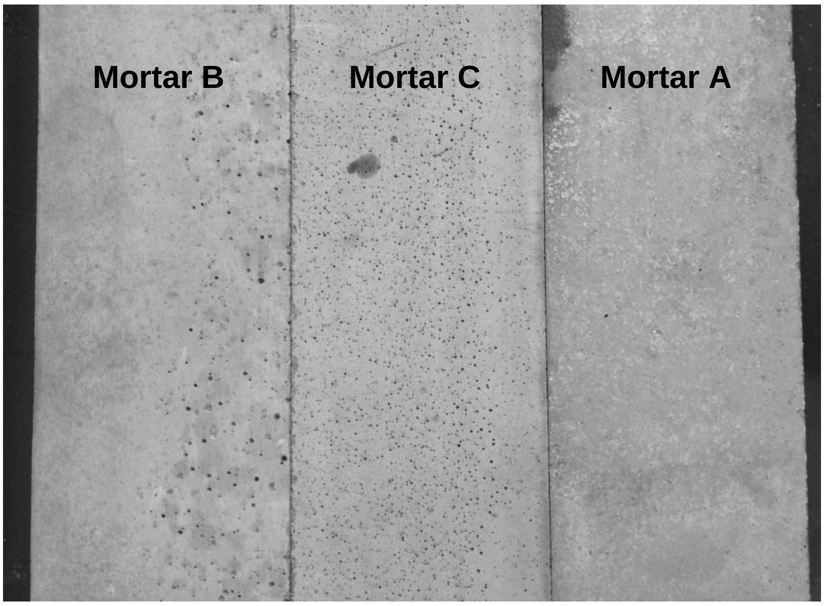

Fig. 9 Visual appearance of the three mortar surfaces after removing the formwork. The air bubbles in Mortar B were estimated to have an average diameter of 5 mm, whereas they were estimated to have an average diameter of 2 mm for Mortar C, and 0.5 mm for Mortar A. From the photo it can be seen how the air bubbles in Mortar B were mainly located in one side of the mortar joint whereas they were more evenly distributed over the surface of Mortar C. In Mortar A very few air bubbles were seen.

Air bubbles are clearly present at the surface of Mortar B and Mortar C as seen from Fig. 9. The air bubbles in Mortar B were largest. They were estimated to have an average diameter of 5 mm and the largest air bubble present had a diameter of 12 mm. These air bubbles were primarily located at one side of the mortar joint. For Mortar C the air bubbles were more evenly distributed over the surface of the mortar joint and their diameter was smaller compared to Mortar B. The average diameter was estimated to be 2 mm and the largest air bubble had a diameter of 3 mm. For Mortar A only very few air bubbles were present and all had a diameter less than 1 mm.

5 Discussion

When post-tensioning the Pearl-Chain arch substructure the strength of the mortar joints should be 5 MPa to be able to transfer the post-tension forces. From Fig. 6 it can be seen that all mortars have met this requirement after 1 day which means that their strength is sufficient to post-tension the arches. The concrete used in the substructure has a 28 days compressive strength of 55 MPa. Hence, the 28 days compressive strength of all three mortar products exceeds the compressive strength of the concrete. This implies that the mortar products which have been examined will all provide a stronger joint than concrete in terms of compressive strength.

When comparing the measured compressive strengths and the corresponding characteristic values it should be kept in mind that the mixer used to produce specimens to determine the measured strengths and the mixer used to determine specimens to determine the characteristic strengths differ. It is well known that the type of mixer will have a big influence on the outcome. Hence, when a Hobart mixer is used to characterise the strength of e.g. Mortar A, according to Table 1, it is expected that the strength can vary when a compulsory mixer is utilized instead. This is believed to cause the differences seen in Fig. 6. Therefore, the mixing was repeated to determinate the compressive strength completely in agreement with EN 196-1. Fig. 10 shows the results. It is seen that the compressive strength after 1 day and after 7 days are now meeting the characteristic values when considering the average values and the standard deviation. However, the mortar used for the Pearl-Chain Bridge application is believed to obtain the strength in Fig. 6, assuming that the same 40 l compulsory mixer is used.

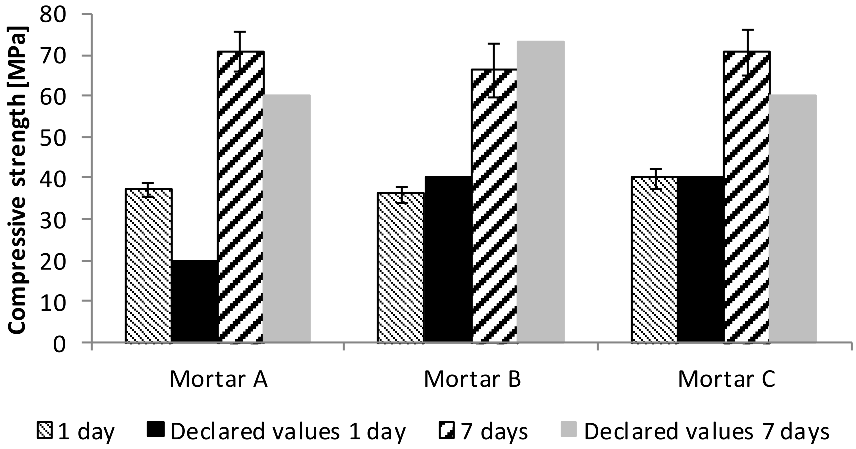

Fig. 10 1 day and 7 days compressive strengths determined from EN 196-1 when Mortar A, Mortar B and Mortar C have been mixed in a Hobart mixer. Measured values and declared values are shown. The measured values are based on six specimens each.

The homogeneity of all three mortar joints is good. This is observed from the variation in rebound values as well as from the variation in density throughout the mortar joints. In both cases the variation is found to be insignificant for all three mortar joints. This is also confirmed from the bleeding measurement. No bleeding is observed which means that no separation has taken place. This indicates a homogeneous mortar.

However, from the visual inspection big differences were observed between Mortar A and Mortar B/C. The last-mentioned had several air bubbles over the surface of the mortar joints which was not the case for Mortar A. The presence of air bubbles is very critical regarding durability of the mortar joints since the air bubbles provide easy access for water and chloride ingress. Furthermore, they weaken the bond strength between mortar and concrete. The air bubbles discovered in the surface of particularly Mortar C is believed to be caused by its expansive nature. Within the first 15 min. after casting the mortar joint its top surface raised several mm as seen in Fig. 11. It is expected that a certain amount of air is trapped in the mortar with such a significant expansion.

Fig. 11 Visual assessment of expansion of Mortar C. The photo shows the top of the formwork. After casting Mortar C it was leveled out. During the first 15 min. after casting the mortar raised several mm as can be seen from the photo.

Hence, considering this accumulation of air bubbles in the surface of Mortar B and Mortar C, the final choice of the mortar used for application in Pearl-Chain Bridge was Mortar A.

6 Future work

After having selected the most appropriate mortar product concerning homogeneity and strength for the mortar joints in Pearl-Chain Bridges, the next step is to test the durability of the mortar joints. Hence, in future work, full scale mortar joints are cast between SL-Deck Elements. After hardening, cores are drilled from the specimens. These cores are exposed to capillary suction, chloride migration, freezing and thawing and strength tests. Mortar cores, concrete cores and combined concrete/mortar cores are drilled and tested. Any problems and irregularities in the mortar joints can be clarified by comparing the durability properties determined for the different cores. A journal paper will be published later this year concerning the durability tests of the mortar joints.

7 Conclusions

In the present study it has been found that it is possible to cast homogeneous 2.40 m high mortar joints when the mortar is poured from the top so it has a placing depth of 2.40 m. The homogeneity has been investigated for three commercialized high-strength, expansive, self-compacting mortar products and assessed from comparison of variation in rebound values, variation in density, and separation. In spite of homogeneity of all three mortars, a clear difference was observed in the visual appearance of the mortars. Two out of the three mortars had a significant amount of air bubbles encapsulated in the surface. This indicates problems with entrapped air and it is a severe concern regarding durability of the mortars. Based on this, the mortar product which did not experience problems with entrapped air was selected for the application in Pearl-Chain Bridges.

Finally, the strength of all mortars fulfilled the requirements to the strength of the mortar joint. The 1 day compressive strengths exceeded 5 MPa and the 28 days compressive strengths exceeded 55 MPa. The type of mixer used to mix the mortars was seen to influence the strengths; however, the requirements were also fulfilled when using a compulsory mixer. This type of mixer is expected to be used when casting the mortar joints in Pearl-Chain Bridges.

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