FEASIBILITY OF USING SHAPE MEMORY ALLOYS TO DEVELOP SELF POST-TENSIONED CONCRETE BRIDGE GIRDERS

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FINAL REPORT

FEASIBILITY OF USING SHAPE MEMORY ALLOYS TO DEVELOP SELF POST-TENSIONED CONCRETE BRIDGE GIRDERS

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16. Abstract

Post-tensioned (PT) structural elements are used quite often in bridges due to their ability to span long widths economically while providing an aesthetically pleasing structure. PT systems are also preferred in bridge construction because they greatly increase structural capacities and are fairly easy to implement effectively. Although PT systems provide many advantages for designers and constructors, these systems have raised concerns regarding corrosion of the PT tendons. The degree of corrosion of PT tendons is critical to the structural performance of PT systems and the cost to replace tendons can exceed several hundred thousand dollars per tendon. Shape memory alloys (SMAs) are a class of smart materials that have unique properties such as excellent re-centering ability, good energy dissipation capacity, excellent fatigue resistance, and high corrosion resistance. This project investigated the feasibility of developing self post-tensioned (SPT) bridge girders by activating the shape memory effect of SMAs using the heat of hydration of grout. In particular, the project investigated the temperature increase due to the heat of hydration of grout. A typical plastic cylinder was filled with grout at room temperature to monitor the temperature inside the duct during the grout's hydration. Three commercially available grouts were considered in the tests: Euclid, Sika Grout 300 PT, and Five Star Special Grout 400. The grouts were mixed in accordance with the manufacturer's recommendation. A single steel tendon was placed in the center. A thermocouple was attached at that tendon within the duct to measure the temperature. A data acquisition system was used to collect the temperature data for 48 hours. The variation of the temperature versus time was examined.

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INTRODUCTION

Post-tensioning is a form of active steel reinforcement used in concrete construction. It is considered active since the steel resists tension before concrete on the tension face begins cracking (Post-Tensioning Institute, 2000). This is achieved by placing steel tendons in pre-positioned ducts in a concrete beam. The tendons are stressed through jacking, and the stressed tendons are anchored, applying a compressive force on the tension face of a beam and preventing concrete cracking.

Post-tensioned (PT) structural elements are used quite often in bridges due to their ability to span long widths economically while providing an aesthetically pleasing structure. PT systems are also preferred in bridge construction because they greatly increase structural capacities and are fairly easy to implement effectively. Although PT systems provide many advantages for designers and constructors, these systems have raised concerns regarding corrosion of the PT tendons. The degree of corrosion of PT tendons is critical to the structural performance of PT systems, and the cost to replace tendons can exceed several hundred thousand dollars per tendon.

With increasing demands for high structural performance, the use of "smart material" has been considered in various engineering disciplines due to the appealing characteristics of these materials, including efficiency, self-actuation, adaptability, self-monitoring and self-healing, and decision making. Recently, shape memory alloys (SMAs) have received considerable attention as a class of smart materials that can be employed in bridge engineering applications (Ozbulut et al., 2011). SMAs have the ability to regain their original shape after being deformed up to 6-8% strain. This shape recovery is a result of an underlying reversible solid-solid phase transformation, which can be induced by either a stress or a temperature change.

Several researchers have investigated the use of SMAs in prestressing applications. Among these, Maji and Negret (1998) were the first to utilize the shape memory effect in NiTi SMAs to induce prestressing in concrete beams. SMA strands were activated by heating them with an applied voltage. El-Tawil and Ortega-Rosales (2004) tested mortar beam specimens prestressed with SMA tendons. SMA tendons were heat-triggered to induce a post-tensioning effect. Test results showed that significant prestressing could be achieved. Sawaguchi et al. (2006) investigated the mechanical properties of mini-size concrete prism specimens prestressed by Fe-based SMAs.

The previous studies have been focused on thermally activating NiTi SMA tendons by electrical heating and have been mostly at the theoretical and laboratory study levels. The present study investigates the feasibility of developing self post-tensioned bridge girders by activating the shape memory effect of SMAs using the heat of hydration of grout. In particular, this initial experimental work evaluates the temperature increase due to the heat of hydration of grout.

RESEARCH APPROACH

Significant heat is generated during the hydration of cement products. Numerous factors such as the type and composition of cement, the proportion of the mix, and the ambient temperature affect the heat evolution during the hydration process. In concrete structures, internal temperatures of 70°C are not uncommon (Dwairi et al., 2010). In grouting applications, higher temperatures can be developed, since the grout generally is composed of a very high portion of cement and heat dissipation is mostly restricted. Temperature rises over 80°C have been observed in grouting applications (Vinidex Pty Limited, 2002; Molz and Kurt, 1979).

SMAs have four characteristic temperatures at which phase transformations occur: (1) the austenite start temperature A_s, where the material starts to transform from twinned martensite to austenite; (2) austenite finish temperature A_f, where the material is completely transformed to austenite; (3) martensite start temperature M_s, where austenite begins to transform into twinned martensite; and (4) martensite finish temperature M_f, where the transformation to martensite is completed. If the temperature is below M_s, the SMA is in its twinned martensite phase. When a stress above a critical level is applied, the material transforms into detwinned martensite phase and retains this phase upon the removal of the load. It can regain its initial shape when the SMA material is heated to a temperature above A_f. Heating the material above A_f results in the formation of the austenite phase and a complete shape recovery. By a subsequent cooling, the SMA transforms to the initial twinned martensite phase without any residual deformation. Figure 1 illustrates the shape memory effect on a stress-strain curve and a temperature diagram.

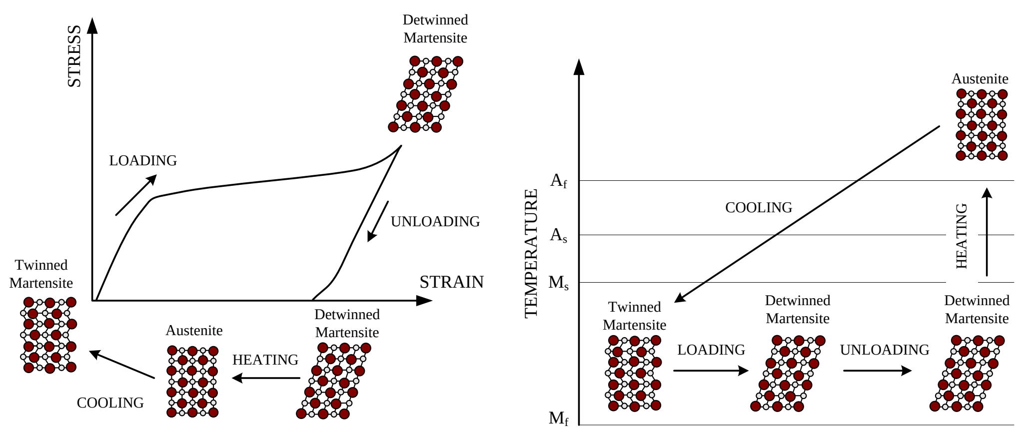

Figure 1. Shape memory effect

Figure 2 illustrates the conditions on the phase transformation temperatures for self-stressing application. There are four characteristic temperatures at which phase transformations occur: (1) the austenite start temperature A_s, where the material starts to transform from twinned martensite to austenite; (2) austenite finish temperature A_f, where the material is completely transformed to austenite; (3) martensite start temperature M_s, where austenite begins to transform into twinned martensite; and (4) martensite finish temperature M_f, where the transformation to martensite is completed. The required temperature window of SMAs for self-stressing application is described as follows:

- The pre-strained SMA tendons must stay in the martensite state at ambient temperature. This will prevent them from recovering their deformations at the storage temperature or during the installation of tendons to the columns. Therefore, the A_s should be higher than the highest possible ambient temperature.

- The M_s should be below the lowest possible ambient temperature. This will ensure that the heated SMA tendons maintain their recovery stress after cooling to the ambient temperature. If the temperature of the SMA tendons becomes lower than the M_s temperature, the SMA tendons will lose their recovery stress due to a phase transformation to martensite. This requirement for M_s coupled with the aforementioned requirement for A_s necessitates the use of the current NiTiNb class of wide-hysteresis (i.e., $\Delta T_H = A_s - M_s$) SMAs.

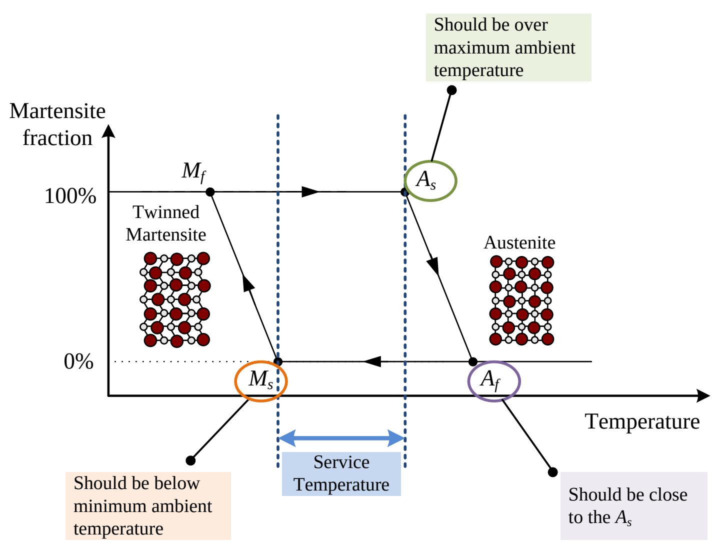

Figure 2. Phase transformation temperatures of SMAs

Also, the A_f should be as close as possible to the A_s, which requires minimizing the differential $\Delta T^{M \rightarrow A} = A_f - A_s$, to complete the phase transformation using the hydration heat. When the temperature rises over the A_s, the SMA tendons start to transform to austenite, and thus recovery stresses are induced. However, the maximum recovery stress will not be obtained until the microstructure is completely austenitic, at a temperature over the A_f.

Figure 3 shows the process for the self post-tensioning (SPT) concrete girder using SMAs. First, the SMA tendons, in the martensitic state, are pre-strained. Then, concrete is poured and after hardening, the SMA tendons are installed in post-tensioning ducts. The voids between the ducts and the SMA tendons are then filled with grout. Due to the heat of hydration of grout, the temperature of the SMA tendons increases, which induces the transformation to austenite when the temperature is over the A_s. A complete transformation to austenite phase occurs when the temperature reaches the A_f. As the SMA tendons attempt to return back to their original shorter length, while being constrained at both ends, a tensile stress is produced in the tendons, causing pre-stress in the column.

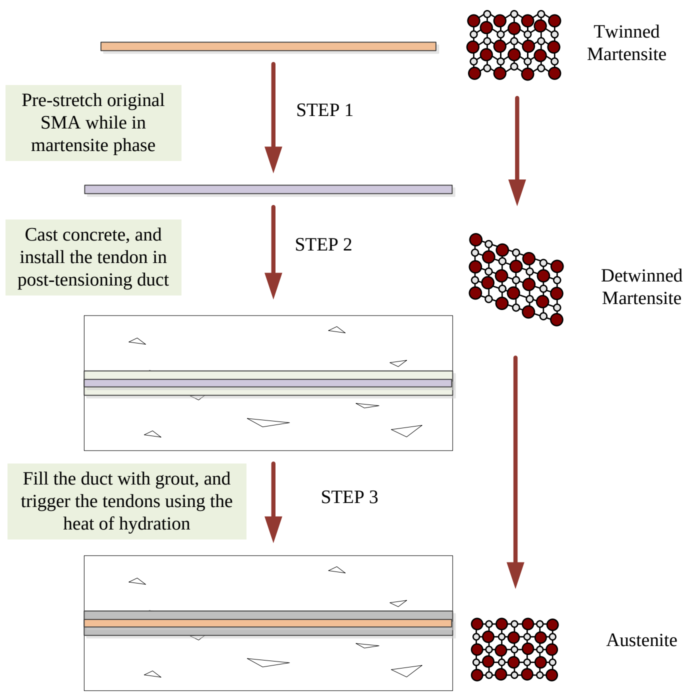

Figure 3. Self post-tensioning process

The goal of this project is to monitor the temperature increases due to the heat of hydration of grout. Portland cement, potable water, and admixtures are the basic grout materials. The chemical reaction between Portland cement and water is exothermic, i.e. producing heat. This heat is called the heat of hydration. Depending on the need, the heat of hydration can be minimized or maximized by material selection.

EXPERIMENTAL PROCEDURE

In this project, three brands of tendon grout were tested to characterize their heat of hydration. These grouts include: Euclid, SikaGrout 300 PT, and Five Star Special Grout 400. A large mixing cylinder was cleaned and one 3200 g bag of Euclid was put into the cylinder. Then, 800 g of water was added so that the water-to-bag ratio was 0.25, and the contents were mixed in the cylinder for 3 minutes using a high shear Jiffler mixer attached to a Milwaukee Magnum Drill at 2,500 rpm. Timing started as soon as water was added into the mixing cylinder. The resulting grout mixture was then poured into a 4-inch-by-8-inch cylinder with a single tendon placed in the center, and the cylinder was capped. On this tendon, a thermocouple was attached. The thermocouple was then connected to a Campbell Scientific data logger which monitored the temperature of the curing grout every minute for 48 hours. This procedure was repeated for the SikaGrout 300 PT with the exception of the water-to-bag ratio, which was 0.24. This process, which is illustrated in Figures 4 through Figure 10, was completed once more for each grout brand, resulting in three trials for Euclid and SikaGrout 300 PT and two trials for Five Star grout.

Figure 4. Adding water to grout mixture and start of mixing/timing.

Figure 5. Mixing grout with high shear Jiffler mixer.

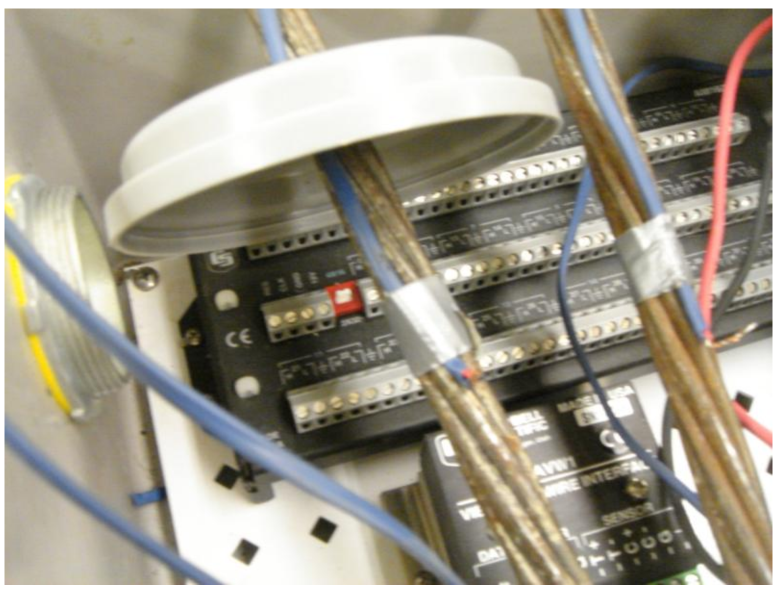

Figure 6. Thermocouple attached to steel tendon.

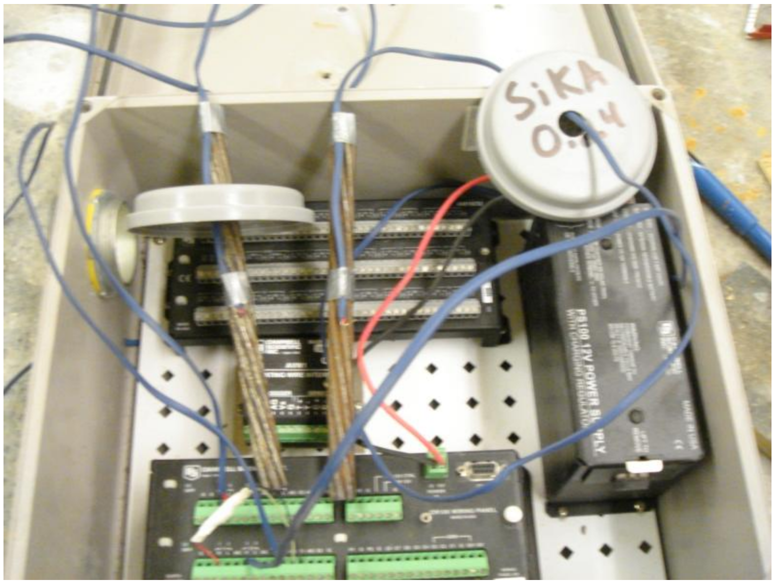

Figure 7. Thermocouples on steel tendons and the data logger.

Figure 8. After pouring grout into 4” x 8” cylinder, steel tendon is placed inside, and it is capped.

Figure 9. Completed sample during temperature collection period.

Figure 10. Both samples are left to cure while temperature data are collected.

EXPERIMENTAL RESULTS

The tests on Euclid and Sika grouts were conducted three times on different days. In the first trial, it was found that Sika Grout 300 PT reached the higher temperature of the two during curing with a temperature of 48°C. The Euclid mixture peaked at 41°C and had two spikes, both before the 48°C peak of Sika (Figure 11). In the second trial, Sika again reached the higher temperature of 53°C. Interestingly, the Sika peak of the second trial occurred about 200 minutes earlier than the Sika peak of the first trial (Figure 12). In the third trial, both types of grouts reached the same peak temperature observed in the first trial (Figure 13). The tests on Five Star Grout 400 were conducted twice. As shown in Figure 14, the maximum temperature reached during both tests was 41°C. The results of the experimental tests are summarized in Table 1.

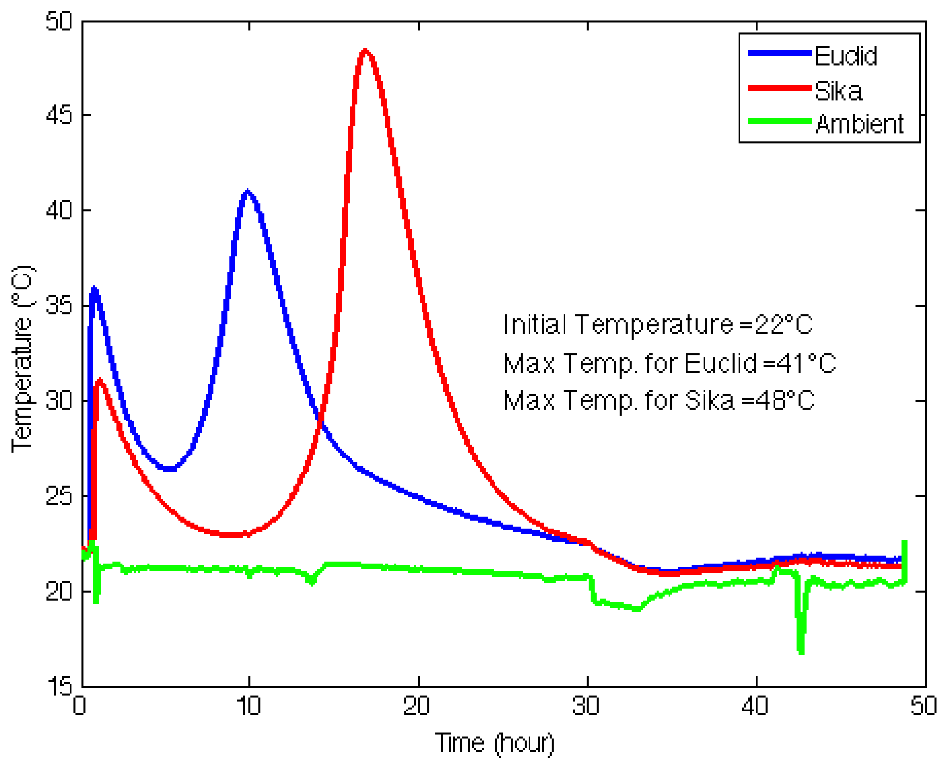

Figure 11. Temperature rise during first trial of Sika and Euclid grouts test.

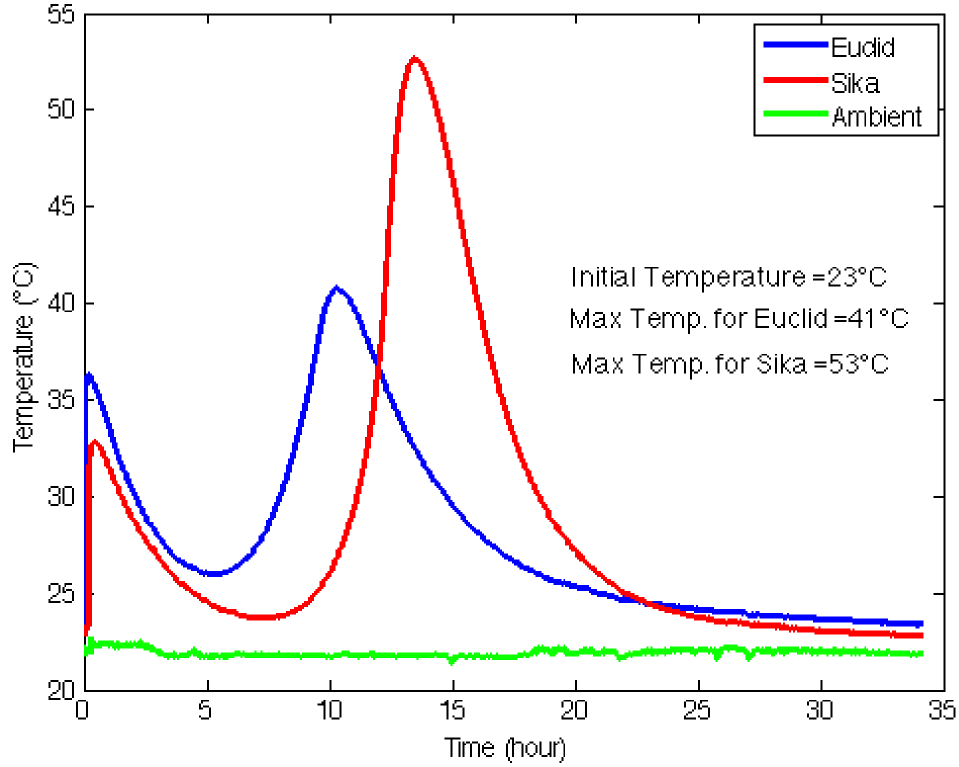

Figure 12. Temperature rise during second trial of Sika and Euclid grouts test.

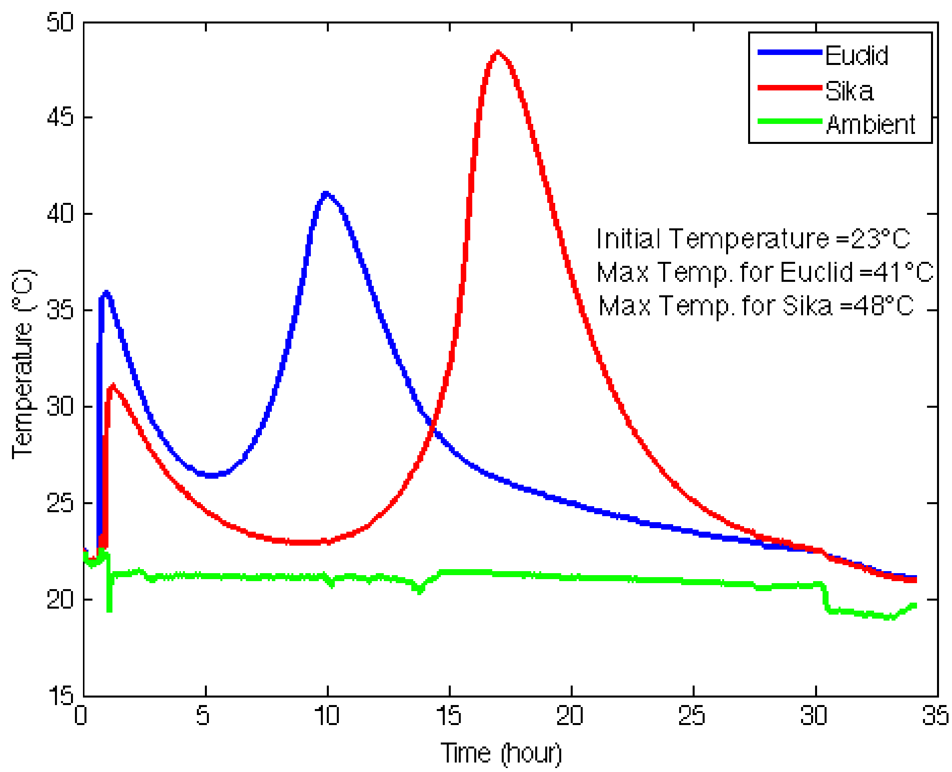

Figure 13. Temperature rise during third trial of Sika and Euclid grouts test.

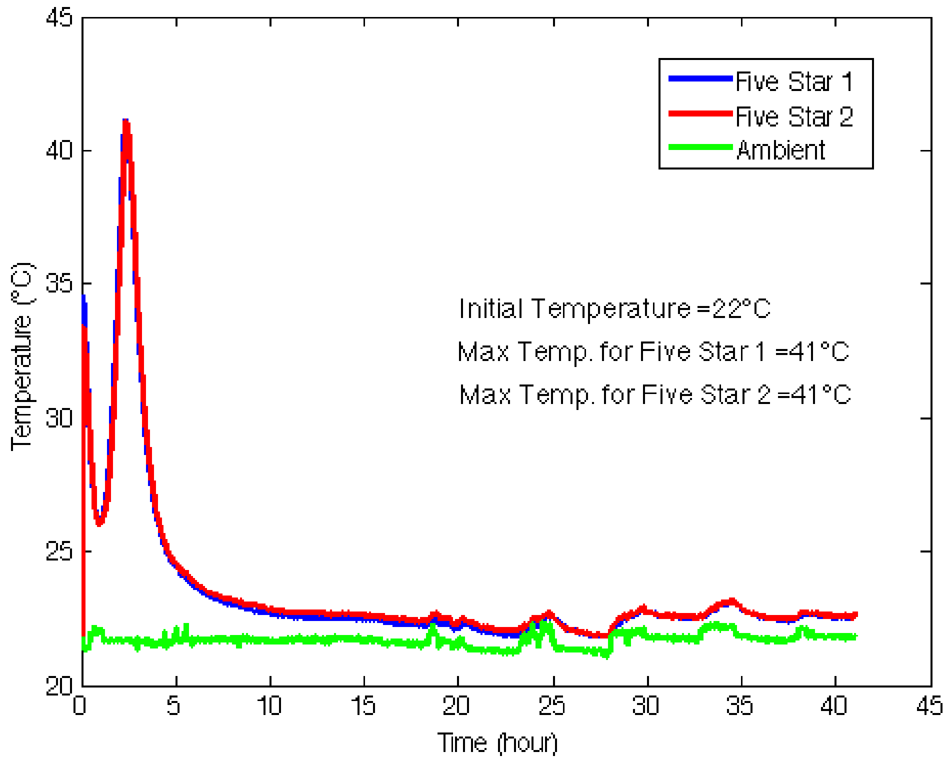

Figure 14. Temperature rise during first and second trial of Five Star grout test.

Table 1. Experimental test results.

Test No	Grout	Initial Temperature (°C)	Maximum Temperature (°C)	Temperature Increase (°C)
1	Euclid	22	41	19
2	Euclid	23	41	19
3	Euclid	23	41	19
4	Sika 300 PT	22	48	26
5	Sika 300 PT	23	53	30
6	Sika 300 PT	23	48	25
7	Five Star Grout 400	22	41	19
8	Five Star Grout 400	22	41	19

CONCLUSIONS AND RECOMMENDATIONS

This project investigated the feasibility of activating SMA tendons using heat of hydration of grout in order to develop self post-tensioned concrete bridge girders. In particular, the temperature increases during the hydration of three commercially available grouts were evaluated. A typical 4-inch-by-8-inch cylinder specimen was filled with the grout. A steel tendon was placed to the center of the cylinder. A thermocouple and a data acquisition system were employed to measure the temperature during 48 hours. Time versus temperature plots were created for each test. It was observed that the largest temperature increase was for the Sika grout. At three different tests of Sika grout, an average of 27°C temperature increase was observed. The temperature increases for both Euclid and Five Star grouts were 19°C. The results indicate that a commercially available grout can provide considerable temperature increase during the heat of hydration of grout, which can be used to activate SMA tendons.

The use SMA tendons, which possess high fatigue and corrosion resistance, as post-tensioning elements in concrete girders will increase the service life and life-cycle cost savings for concrete bridges. The replacement of steel tendons with SMA prestressing tendons will prevent corrosion-induced deterioration of tendons in concrete structures. The use of heat of hydration of grout to activate the shape memory effect of SMA tendons will provide self-stressing capability. This will greatly simplify the tendon installation. The need for jacking equipment or electrical source will be eliminated. This will also enable the reinforcement to form in any shape in two- or three-dimensional space without special devices. The use of SMA tendons will lead to better control of the prestress and higher levels of effective prestress. During the service life of a bridge, heat-triggering the SMA tendons can repair possible damage observed in girders and reduce excessive deflections.

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