Development of Prestressed Concrete Using Fe–Mn–Si-Based Shape Memory Alloys Containing NbC*

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This article reports the mechanical properties of concrete prestressed by the Fe–Mn–Si-based shape memory alloys containing NbC that exhibit an excellent shape memory effect without the so-called ‘training’ treatment. A thermomechanically treated Fe–28Mn–6Si–5Cr–0.53Nb–0.06C (mass%) alloy was used for this purpose. Four square bars of the alloy were embedded in mortar, and heated above their reverse martensitic transformation start temperature after hardening of the mortar matrix. Three-point bending tests were performed for the mechanical property characterization. It was found that prestressing by the shape memory alloys increased the bending strength and cracking stress of the mortar.

Keywords: prestressed concrete, shape memory alloy, iron–manganese–silicon-based alloy, niobium carbide, cracking stress, smart composite

1. Introduction

Concreting materials have an excellent compressive strength but lower tensile strength, bending strength, stiffness and toughness when compared to metallic materials. For a long time, steel rods have been widely used in reinforced concrete. Various kinds of advanced reinforced concretes, such as fiber concrete and prestressed concrete, have also been developed and infiltrated.¹ The fiber concrete is reinforced with short carbon or steel fibers, and is used in components such as slabs and claddings, which undergo large bending loads. The prestressed concrete is reinforced by so-called PC steel rods or cables, which are made of high tension steels and elastically pre-extended. The tension of the PC steel rods is relieved after hardening of concrete to produce the compressive stress in the concrete matrix, which significantly improves the tensile strength of concrete. Recently, the prestressed concrete has become popular and used especially in long span constructions.

Smart composites, which utilize large shape recovery loads of shape memory alloys (SMAs), have also been proposed.²⁻⁸ For example, the SMA prestressed concrete can be produced through the following four steps: 1) pre-straining of SMAs, which induces the martensitic transformation, 2) installing the SMAs into freshly mixed concrete, 3) hardening the concrete, and 4) heating the SMAs to generate a shape recovery stress, which acts as a prestress. The above process is different from that of the conventional prestressed concrete, and therefore, a unique construction technique is possible.

Non-thermoelastic iron-based SMAs, such as Fe–Mn–Si-based alloys,⁹⁻¹⁴ are favorable for this kind of application due to their wide temperature hysteresis. The cost efficiency of the Fe–Mn–Si-based alloys relative to the conventional SMAs is also an advantage for practical use as a structural material. Watanabe et al. fabricated an SMA fiber/plaster smart composite, using Fe–27.2Mn–5.7Si–5Cr (mass%) alloys, and reported that the mechanical properties of the plaster was improved by the compressive stress due to the shape recovery force of the SMA fibers.¹⁵ However, there is no other report so far on the reinforcement of concreting materials using the Fe–Mn–Si-based SMAs, in spite of its cost efficiency and high potential.

Kajiwara et al. reported that the shape memory properties of Fe–Mn–Si-based SMAs can be improved by the fine dispersion of NbC carbides.¹²⁻¹⁸ These newly modified SMAs not only have the advantages of low cost and a large shape recovery strain, but also exhibit a very high recovery stress above 300 MPa by some simple thermomechanical treatments. The latter fact indicates that the SMAs are preferable for prestressing concreting materials utilizing the recovery stress. In this study, we investigated whether the NbC-containing Fe–Mn–Si-based SMAs are capable of prestressing the concreting materials. First, in the following section, we will briefly describe some characteristics of the NbC-containing SMAs in connection with prestressing the concrete. The fabrication procedure of an SMA prestressed mortar¹⁹ and its mechanical properties will then be described in sections 3 and 4, respectively, and the summary and future prospective will be given in the section 5.

2. Shape Memory Properties of NbC-Containing Fe–Mn–Si-Based Alloys

It is well known that the shape memory properties of Fe–Mn–Si-based SMAs are significantly improved by a special thermomechanical treatment called ‘training’, which consists of a repetitive slight deformation and subsequent heating.¹⁰ The performance of the alloys reaches the level of practical use by this training, but this complicated process raises the manufacturing cost and limits the shape of the SMA components.

On the other hand, a feature of the NbC-containing Fe–Mn–Si-based SMAs is that the alloys exhibit good shape
memory properties comparable to those of the training treated Fe–Mn–Si-based SMAs, without being subjected to the training.12,13) The key to obtaining good shape memory effects is the fine dispersion of the NbC precipitates inside the austenite grains. Pre-deformations, such as warm or cold rolling prior to the aging, are effective for further improvement of the shape memory properties by further refining the NbC carbides into several nanometer size.14–18) As a result, the shape recovery strain of 4% and the shape recovery stress of 300 MPa were achieved. The thermomechanical treatment consisting of the pre-deformation and aging is simpler than the training, and thus the manufacturing cost can be reduced. It is also an advantage that the new process allows one to design various shapes of the SMA devices and components. Moreover, the shape recovery stress, which is the most important parameter for prestressing, can be controlled and improved by the thermomechanical treatment of the NbC-containing SMAs. As a consequence, it is concluded that the NbC-containing Fe–Mn–Si-based SMAs are suitable for prestressing the concrete.

3. Fabrication of SMA Prestressing Mortar

Mini-size prism specimens (\(W \times 20 \text{mm} \times T \times 20 \text{mm} \times L \times 80 \text{mm}\)) of the mortar reinforced by an NbC-containing Fe–Mn–Si-based SMA were fabricated, and their mechanical properties were evaluated by three-point bending testing.

The chemical composition of the alloy used for the reinforcements is Fe–28Mn–6Si–5Cr–0.53Nb–0.06C (mass%), in which the best shape memory property was obtained. After vacuum induction melting, hot-forging and rolling, a solution treatment was carried out at 1470 K for 10 h. A thermomechanical treatment, consisting of 14% warm-rolling at 870 K and subsequent aging at 1070 K for 10 min, was then performed in order to improve the shape memory properties by producing fine precipitates of the NbC carbides. Square bars of the SMA with the dimensions of \(W \times 4.0 \text{mm} \times T \times 2.0 \text{mm} \times L \times 75 \text{mm}\) were spark cut and deformed by tensile strain to 5%. A thick plate with the same alloy composition as the SMA bars, and the mortar prism without reinforcement, were also prepared for comparison. For each SMA prestressing mortar, stainless reinforced mortar, and the mortar without reinforcement, two prisms cured at 450 K and one prism cured at 520 K were prepared.

Compression tests were carried out to investigate the mechanical properties of the mortar matrix, which was subjected to a higher temperature during the autoclave curing than that in the usual curing processes to obtain the prestress by generating a shape recovery stress. The cylindrical mortar specimens without reinforcement with the dimensions of \(\Phi 50 \text{mm} \times 100 \text{mm}\) and \(\Phi 40 \text{mm} \times 80 \text{mm}\) were used in the compression tests.

4. Mechanical Properties of SMA Prestressing Mortar

4.1 Shape memory properties of SMA reinforcements

To measure the shape recovery stress, the specimens were subjected to 5% strain and fixed in a mechanical testing machine, and then heated to 670 K and cooling to room temperature in an infrared furnace attached to the mechanical testing machine. Figure 3 shows the recovery stress-temperature characteristics of the Fe–28Mn–6Si–5Cr–0.53Nb–0.06C alloy, which was subjected to 14% rolling at 870 K followed by aging at 1070 K for 10 min. Upon heating, the reverse martensitic transformation starts at about 360 K and the shape recovery stress is generated under the constrained condition. The recovery stress increases with the increasing temperature, and reaches 190 MPa at 670 K. Upon cooling, a
further increase in the stress is caused by the thermal construction of the specimen, resulting in the recovery stress of 250 MPa at room temperature.

The above result can be obtained when the specimen is heated to a sufficiently high temperature. However, when the specimen is heated to 450 or 520 K, the variations in the recovery stress upon cooling follow the curves indicated by the dotted lines in Fig. 3. Therefore, the prestresses formed in the SMA reinforced mortar are thought to be 80 and 130 MPa for the curing temperatures of 450 and 520 K, respectively.

### 4.2 Mechanical properties of the mortar matrix

Figure 4 shows the results of the compression tests for the mortar without reinforcement. The compressive strength for the 450 K curing was obtained by averaging the results of three specimens. It was found that the compressive strength for the 520 K curing was slightly lower than that for the 470 K curing.

![Fig. 3 Change in shape recovery stress upon heating above reverse transformation temperature and subsequent cooling to room temperature for Fe–28Mn–6Si–5Cr–0.53Nb–0.06C (mass%) alloy. The sample was pre-rolled by 14% at 870 K and aged at 1070 K for 10 min.](image1)

Further strengthening is expected when a higher recovery stress, i.e., higher prestress, can be achieved by further heating to a higher temperature. However, the bending strength and cracking stress of the specimen cured at 520 K showed no significant difference with those of the specimen cured at 470 K. A possible reason is the degradation of the mortar matrix due to the higher than normal curing temperature. The results suggest that lower reverse martensitic

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Figure 5 shows the bending load-displacement curves of the SMA reinforced, stainless reinforced, and non-reinforced specimens. The displacements, when the cracking starts, are denoted by downward arrows in the figure. Figures 6 and 7, respectively, summarize the bending strengths and cracking stresses of all the specimens, which were obtained from the curves in Fig. 5. It is obvious that both the bending strength and cracking stress were increased using the SMA as compared to the stainless reinforced and non-reinforced specimens. The reinforcement may be accomplished by the prestress due to the recovery stress of the SMA heated under a constraint in the hardened mortar matrix.

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transformation temperatures are required for obtaining higher recovery stresses (prestresses) avoiding severe thermal damage to the concrete matrix.

5. Summary

Mini-size prism specimens of the SMA reinforced mortar were fabricated and their mechanical properties were measured. The NbC-containing Fe–Mn–Si-based SMAs were used for this purpose, since they are suitable for this application due to their low cost and high recovery stress. It was revealed that the iron-based SMAs are useable for producing the prestress in the mortar. Further strengthening can be achieved by lowering the reverse transformation temperatures of the SMAs, thus avoiding significant thermal damage to the mortar matrix.

The price per unit volume of the prestressed concrete is dominated by the price of the reinforcements rather than that of the concrete. Therefore, it is meaningful that the concrete was successfully reinforced by a low cost Fe–Mn–Si-based SMA containing NbC. Using this new technique, the three-dimensionally reinforced concrete prestressed by randomly oriented SMA fibers can also be produced, which is impossible in the conventional prestressed concrete using high tension steel.

REFERENCES

19) The cementitious materials containing coarse aggregates larger than 5 mm are called `concrete', while those containing aggregates less than 5 mm are called `mortar'.