Fatigue and Structural Performance Evaluation of Fast-Drying Ultra-High Strength Grout Material

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Abstract
In this study, a fast-drying ultra-high strength grout material was developed. The physical properties, fatigue performance, and failure mechanism of the newly developed grout material were clarified through quality inspections and uniaxial cyclic compression tests of several prepared specimens. Uniaxial compressive loading tests were conducted on small-scale models with and without shear keys in order to assess the structural performance of the newly developed grout material. The newly developed grout material and an existing high-performance grout material were compared, and the test results showed that the newly developed grout material had outstanding advantages with regard to the setting time, fatigue performance, and structural performance compared to the latter.

Keywords: fast-drying ultra-high strength grout material; fatigue performance; structural performance; uniaxial cyclic compression

1. Introduction
In general, high-strength grout materials are used to maintain underwater structures, fix offshore structures with anchor bolts and fill gaps between a machine and the concrete slab of a plant. In particular, they are broadly used to enhance the anchorage capacity and bearing capacity of supports in civil structures. Over the past few decades, interest in new sources of renewable energy has increased globally, and many researchers have considered the effective design of offshore wind power structures subjected to fatigue loads such as wind, waves, and earthquakes. Accordingly, research on the fatigue performance of normal- and high-strength grout materials (Holmen 1982) and on the structural performance and failure mechanism of offshore structures (Billington and Lewis 1978; Hordyk 1996; Schaumann and Wilke 2006; Prakhya et al. 2012; Lotsberg et al. 2012) has been on-going since the 1970s. Ingebrigtson (1990), Schaumann and Wilke (2006), and Lotsberg et al. (2012) proposed various fatigue design methods for grouted pile sleeve connections of offshore structures based on previous studies on the mechanical properties of varied grout materials. Lately, many researchers have reported on the structural performance of offshore structures with high-performance grout materials; however, few researchers have considered material characteristics such as the fatigue and structural performance of high-strength grout materials, which are required to assess the bearing capacity or anchorage capacity of offshore structures (Lohaus et al. 2006; Sørensen 2009). A safe and effective design is needed for the bearing capacity and sleeve connections of offshore structures because they have become slimmer, larger and more complex with the increased strength of advanced structural materials. However, there has been relatively little research on the physical properties and failure mechanism of grout materials compared to other offshore structural components.

This study examined the physical properties and failure mechanism of a newly developed, fast-drying and ultrahigh-strength grout material for the pile/sleeve connections of offshore wind turbine structures. Uniaxial cyclic compression tests were performed on several specimens, and the results of the newly developed grout material were compared with those of an existing high-strength grout material. In addition, small-scale models were tested under uniaxial compressive loading with and without shear keys to evaluate the structural performance based on the difference in compressive strengths of the grout materials.

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2. Fatigue Performance of Newly Developed Grout Material

The performances of the newly developed grout material are classified in terms of material performance and structural performance. The former simply means its setting time and compressive strength at 1 and 28 days. The latter is the fatigue resistance under cyclic loading. These performances of the material are evaluated in this research. The uniaxial cyclic compression test (fatigue test) for the concrete specimens was conducted as a basic research before conducting future experimental research on the structural performance of full-scale models with various compressive strengths of concrete, diameter and length of a pile/sleeve connection, distance between shear keys and the number of cyclic loadings.

2.1 Material Properties

In this section, the material properties of the newly developed, fast-drying, ultrahigh-strength grout material are introduced followed by its fatigue performance. The newly developed grout material possesses the same basic characteristics as existing grout materials which are employed to connect an offshore wind turbine tower to foundation piles and has a 1-day compressive strength of more than 70 MPa. Table 1 lists the variety and chemical composition of the binders used. The newly developed grout material comprises binders of 50.96%, aggregates (cement) of 40.04% and water of 9.00%. Table 2 lists the results for a quality inspection of the newly developed grout material: the flow test, weight of a unit volume, setting time, compressive strength, flexural strength and rate of change in length.

Based on the results, the setting time of the newly developed grout material is five times shorter than that of the existing grout material, and its compressive strength and flexural strength are 20% and 30% higher, respectively. The quality performance was confirmed to exceed that of the existing grout material and the target objectives which were established in the development stage.

Table 1. Variety and Chemical Composition of Binders

| Density (g/cm³) | Fineness (cm²/g) | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Ig-Loss |
|----------------|------------------|------|-------|-------|-----|-----|-----|--------|
| 2.81           | 8,500 ±500       | 22.13| 11.40 | 1.59  | 45.05| 1.79| 11.10| 3.54   |

Table 2. Results of Quality Inspection

| Sort                | Property                | Requirement | Result Existing material | Result Developed material | Testing method |
|---------------------|-------------------------|-------------|--------------------------|---------------------------|-----------------|
| Fresh state         | Flow (mm)               | -           | 290                      | 310                       | ASTM C939       |
|                     | Weight of unit volume (kg/m³) | -         | 2.41                     | 2.66                      | ASTM C138/C138M-13a |
|                     | Setting time (hour: minute) | -           | 4:45                     | 0:55                      | ASTM C935-10    |
| Compressive strength (MPa) | 1 day              | 34.5        | 58.4                     | 73.8                      | ASTM C109/C109M-13 |
|                     | 3 days              | -           | 86.7                     | 95.3                      |                 |
|                     | 7 days              | -           | 108.2                    | 124.8                     |                 |
|                     | 28 days             | -           | 112.9                    | 142.2                     |                 |
| Hardened state      | Flexural strength (MPa) | 1 day       | 7.9                      | 10.1                      | ASTM C348-08    |
|                     |                       | 3 days      | 12.1                     | 20.4                      |                 |
|                     |                       | 7 days      | 14.7                     | 23.1                      |                 |
|                     |                       | 28 days     | 18.3                     | 26.0                      |                 |
| Rate of length change (%) | 1 day              | 0.0~0.1     | 0.032                    | 0.030                     | ASTM C157/157M-08e1 |
|                     | 3 days              | -           | 0.051                    | 0.044                     |                 |
|                     | 7 days              | -           | 0.058                    | 0.051                     |                 |
|                     | 28 days             | < 0.2       | 0.061                    | 0.055                     |                 |

Table 3. Size and Designed Strength of Specimens

| Specimen | Size     | Design strength | Initial compress load /Fatigue load |
|----------|----------|-----------------|------------------------------------|
| FE-1     | φ50×100mm| 100 MPa         | 36.6 MPa / 3.7 MPa                 |
| FE-2     |          |                 |                                    |
| FD-1     | φ50×100mm| 140 MPa         | 68.3 MPa / 6.8 MPa                 |
| FD-2     |          |                 |                                    |

F: Specimen for fatigue test, E: Existing grout material, D: Developed grout material
2.2 Test Setup

Table 3 lists the specimens evaluated for fatigue performance. Specimens were prepared from the existing high-strength grout material (100 MPa) and the newly developed grout material (140 MPa), and each specimen was 50 mm in diameter and 100 mm in height. Here, FE and FD denote specimens of the existing grout material and newly developed grout material, respectively, for the fatigue test. As shown in Fig. 1., all specimens were compressed by a universal testing machine (UTM) with a 2000 kN capacity to up to about 50% of their maximum strength and then tested under uniaxial cyclic loading at a frequency of 0.3 Hz up to ±10% of the initial compressive load (Sørensen 2011). In total, 60,000 cyclic loads were planned. Fig. 2 shows a mimetic diagram of the wire strain gauges installed in a specimen for the uniaxial cyclic compression test. The axial and transverse strains of specimens were measured by wire strain gauges attached crosswise on both sides of the specimens. Moreover, the axial deformations of specimens under uniaxial cyclic compressive loading were measured by using two linear variable differential transformers (LVDTs).

2.3 Test Results

2.3.1 Time Versus Axial Stress Relationship

Fig. 3 represents the time-axial stress relationships of the representative specimens FE-1 and FD-1. The experimental data were extracted for the 600 s immediately after the start of the test and for the 400 s immediately before the end of the test with a dynamic data logger for fatigue performance evaluation. Fig. 3 shows that the axial stress of the specimen FE-1 and FD-1 linearly increased up to about 50% of the expected maximum strength (36.6 and 68.3 MPa, respectively). After the uniaxial cyclic compressive loading test began, the axial stresses of FE-1 and FD-1 stayed constant at about 34–40 MPa and 62–75 MPa, respectively. However, the ranges of the axial stress amplitude became slightly larger for all specimens before the end of the test. The mean ratios of change in the axial stress amplitude of FE-1 and FD-1 were 50% and 23%, respectively. A similar tendency was also found for specimens FE-2 and FD-2.

2.3.2 Time Versus Axial Displacement Relationship

Fig. 4 shows the time-axial displacement relationships of the representative specimens FE-1 and FD-1. The axial displacement of FE-1 linearly increased up to 1.25 mm and then nonlinearly increased up to 2.0 mm after the start of the uniaxial cyclic compression test. After the test began, the axial displacement amplitudes of FE-1 and FD-1 stayed constant at about 1.97–2.01 mm and 1.95–2.08 mm, respectively. Similar to the time-axial stress relationship, the range of axial displacement became slightly larger before the end of the test. Table 4 compares the changes in the axial displacement for the linear and nonlinear regions and the changes in the axial displacement amplitude after the start and before the end of the test, respectively. The displacement amplitude of the specimens with the newly developed grout material was equivalent to approximately 20% of those of the specimens with the existing grout material. The results of the uniaxial compressive loading test confirmed that the newly developed grout material has an outstanding fatigue performance compared with the existing high-strength grout material.
3. Structural Performance of Newly Developed Grout Material

3.1 Test Setup

Small-scale models of a pile/sleeve connection filled with the existing high-strength grout material and newly developed grout material were tested under uniaxial compressive loading to evaluate the structural performance of the newly developed grout material in the pile/sleeve connections of an offshore wind turbine structure. Table 5 lists the small-scale models and given variables: the design strength of the materials employed and the shear keys installed on the surfaces of the internal and external steel tubes (American Petroleum Institute, 1993). Fig. 5. shows a small-scale model, which consisted of internal and external steel tubes with or without shear keys and with a spacer. Fig. 6. presents the details of the small-scale models. All small-scale models were designed so that the overlapping length and distance between the internal steel tubes ($φ60.3 \times 150 \text{mm}$) and external steel tubes

Table 5. Small Scale Models and Given Variables

| Scale model | Type of grouting material | Design strength of materials | Shear key |
|-------------|---------------------------|------------------------------|-----------|
| SE1-3       | Existing one              | 100 MPa                      | -         |
| SEK1-3      |                           |                              | O         |
| SD1-3       | Developed one             | 140 MPa                      | -         |
| SDK1-3      |                           |                              | O         |

Table 6. Test Results for Small-scale Models without Shear Keys

| Model | Grouted material | Maximum load (kN) | Average of maximum load (kN) | Displacement at maximum load (mm) | Average of displacement (mm) | Note |
|-------|------------------|-------------------|-----------------------------|-----------------------------------|-------------------------------|------|
| SE-1  | Existing material| 11.8              | 14.6                        | 0.30                              |                               |      |
| SE-2  |                  | 18.2              | 14.7                        | 0.45                              | 0.40                          |      |
| SE-3  |                  | 14.2              |                             | 0.46                              |                               |      |
| SD-1  | Developed material| 8.6               | 7.9                         | 0.25                              |                               |      |
| SD-2  |                  | 7.2               | 7.9                         | 0.25                              |                               |      |
| SD-3  |                  | 33.7 (except for SD-3) | 1.10                       |                                   |                               |      |
were 90 and 19 mm, respectively. The shear keys had a height of 1.25 mm and width of 2.5 mm, and they were installed on the outer surface of the internal steel tubes and on the inner surface of the external steel tubes at intervals of 30 mm.

The small-scale model tests were performed by using the UTM of 2000 kN capacity in Fig.1. Uniaxial compressive loads were applied to the small-scale models at a velocity of 0.006 mm/s based on the displacement control method. Two sets of steel strain gauges were installed on the surface of the small-scale models to measure the axial strain, and two LVDTs were set up on both sides of the small-scale models to measure the axial displacement during the test.

### 3.2 Test Results

#### 3.2.1 Small-scale Model without Shear Keys

Fig.7. shows the load–displacement relationships of the small-scale models without shear keys (SE and SD series), and Table 6. lists the results of the uniaxial compressive loading tests: the maximum load, average maximum load, displacement at the maximum load, and average displacement. The average maximum loads of the SE and SD series excluding SD-3 were 14.7 and 7.9 kN, respectively. The average displacements at the maximum load were 0.4 and 0.25 mm, respectively. The strength of the SD series decreased rapidly after the maximum load, in contrast to the SE series. Thus, the SE series had higher resistance to the applied compressive loads rather than the SD series excluding SD-3, even though the SD series had a higher strength. The chemical composition of binders in the SD series may have induced a lower adhesion force between the newly developed grout material and steel tubes compared with the SE series. The results in Table 6. confirm that the grouted materials surrounding the internal tubes subsided from the upper part of the external tube in all small-scale models.

#### 3.2.2 Small-scale Model with Shear Keys

Fig.8. shows the load–displacement relationships of the small-scale models with shear keys (SEK and SDK series), and Table 7. presents the results of the uniaxial compressive loading tests. The average maximum loads of the SEK and SDK series were 131.8 and 213.1 kN, respectively.

The measured strengths of the SEK and SDK series were 8.6 times and 27 times higher, respectively, than those of the SE and SD series. For the small-scale models with shear keys, the average maximum load of the SDK series was about 160% that of the SEK series. The average displacement at the maximum load for the SEK and SDK series were about 10 times larger than those of the SE and SD series. While the strength of the SEK series tended to decrease as the axial displacement increased, the strength of the SDK series repeatedly recovered despite the increasing axial displacement. Fig.9. presents the stress transfer paths in the scale models. The shear keys caused the shear force applied to the scale models to be passed along the stress transfer paths 1–3. Installing shear keys in a scale-model filled with the newly developed grout material enhanced the adhesion conditions between the grouted material and steel tubes and eventually allowed the newly developed grout material to exhibit its own strength under compressive loads. Based on the above test results, if the newly developed grout material is applied to pile/sleeve connections of existing offshore wind turbine structures, their ultimate strength can be improved, and the rapid degradation in the strength of structural members can be prevented.

| Model | Grouted material | Maximum load (kN) | Average of maximum load (kN) | Displacement at maximum load (mm) | Average of displacement (mm) | Note |
|-------|------------------|-------------------|-------------------------------|----------------------------------|-----------------------------|------|
| SE-1  | Existing material| 109.1             | 131.8                         | 2.57                             | 4.29                        |      |
| SE-2  | Developed material| 171.3             | 213.1                         | 5.11                             | 4.29                        |      |
| SE-3  | Developed material| 115.1             | 213.1                         | 5.20                             | 4.29                        |      |
| SD-1  | Developed material| 220.8             | 213.1                         | 2.23                             | 2.94                        | With shear key |
| SD-2  | Developed material| 186.3             | 213.1                         | 2.99                             | 2.94                        |      |
| SD-3  | Developed material| 232.2             | 213.1                         | 3.61                             | 2.94                        |      |
4. Conclusions

Based on the quality inspection of the newly developed grout material, the setting time was confirmed to be five times shorter than that of the existing grout material. Furthermore, its compressive strength and flexural strength were 20% and 30% higher, respectively, than those of the existing grout material. The results of uniaxial compressive loading tests on the specimens and scale models with the newly developed grout material showed that it has great fatigue performance compared with the existing grout material. Finally, even though the chemical composition of the binders included in the new developed grout material may induce a lower adhesion force between the newly developed grout material and steel tubes, installing mechanical shear keys can help improve the ultimate strength of offshore wind turbine structures.
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