Chapter 6  CONCLUSION

As temperature differences are generated in the cross-section of concrete members exposed to fire, the relatively low-temperature deep cross-sectional areas constrain the thermal expansion of the high-temperature areas close to the heated surface, and the elements are in a state of multiaxial stress. However, the multiaxial behavior of plastic strain, the compressive strength under multiaxial stress at high temperatures and the multiaxial behavior of the transient thermal strain have not been elucidated, and no constitutive laws have been constructed for any of them.

It is thought that if constitutive laws which enable the three-dimensional representation of the strain behavior and the compressive strength under multiaxial stress of concrete at high temperatures, the accuracy of the analysis would improve, and it would be beneficial for the evaluation of the strength of the structural members at high temperatures, the prediction of the behavior of the members and the elucidation of the spalling phenomena of concrete at times of fire.

In the present research, aiming at constructing the constitutive laws for ① the multiaxial behavior of the plastic strain, ② the compressive strength under multiaxial stress at high temperatures and ③ the multiaxial behavior of the transient thermal strain, we performed high-temperature compressive strength tests, and the constitutive laws for all of the above were derived from the experimental results. Furthermore, a finite element analysis was performed for the purpose of evaluating the validity and the accuracy of the constitutive laws, and a discussion was provided upon comparing the results of the experiments and the analysis.

Moreover, since the high-temperature characteristics of concrete are strongly influenced by the compressive strength and the type of the aggregate, the constitutive laws derived in the present research cannot be applied in cases where the compressive strength or the aggregate type are different.

The range of applicability of the constitutive laws derived in the present research is compressive strength at ambient temperature of 50 ~ 120 N/mm² (water-binder ratio of 22.5%, 30%, 50%) and temperature up to 800°C, using concrete made with andesite as the coarse aggregate.

6.1 Results of the research

In the present research, the following three constitutive laws were derived for concrete at high-temperatures.

· Plastic flow rule representing the multiaxial behavior of plastic strain
· Failure criterion representing the compressive strength under multiaxial stress
· Flow rule representing the multiaxial behavior of transient thermal strain

In order to account for the volumetric changes in concrete due to plastic deformation when stress is applied, the dilatancy angle of the plastic potential was calculated by applying the flow rules. The dilatancy angle increases together with the stress, and the
existence of stress dependence and temperature dependence, as well as the fact that the angle increases together with the strength of the concrete, was made clear by the experimental results.

Furthermore, it has been made clear that the failure criterion can be expressed in the form of a Drucker-Prager function. In previous elastoplastic analyses, it is common to use the associated flow rule based on the yield surface for the plastic potential of the plastic flow rule with respect to the multiaxial behavior of the plastic strain. The relation between the yield surface and the plastic potential at maximal loading as inferred from the experimental results revealed that plastic strain increment is generated at maximal loading perpendicularly to the yield surface, which indicates that the associated flow rule holds true for maximal loading. However, when the stress is lower, plastic strain increment is not generated perpendicularly to the yield surface at maximal loading, and the associated flow is not applicable.

When the plastic potential, which represents the multiaxial behavior of the plastic strain, is applied to the transient thermal strain, the multiaxial behavior of the transient thermal strain is described with relatively good accuracy, and it was found that the potentials of the transient thermal strain and the plastic strain coincide. The correlations between the three constitutive laws as obtained in the present research are typologically presented in Figure 6.1. The details about the derived constitutive laws are mentioned in the next section.

\[ \text{Compressive strength under multiaxial stress} \]

\[ \text{Yield surface at maximal loading} \]

\[ \text{At maximal loading, the yield surface and the two potentials coincide} \]

\[ \text{Multiaxial behavior of the plastic strain} \]

\[ \text{Plastic potential} \]

\[ \text{Multiaxial behavior of the transient strain} \]

\[ \text{Transient potential} \]

\[ \text{The potentials coincide} \]

\[ \text{The dilatancy angle increases together with the stress} \]

\[ \text{Figure 6.1 Relations between the three constitutive laws as obtained in the present research} \]

### 6.2 Conclusions for each chapter

The results obtained in each chapter are presented below.

**Chapter 2**

This chapter introduces the materials used for the specimens and the method for conducting the high-temperature compressive strength tests in Chapter 3 and Chapter 4. The dimensions and shapes of the electric heater and the loading jig needed for the uniform heating of the specimens are evaluated, wherefore the height of the heater was set to twice the height of the specimens, the specimens and the loading jig were heated simultaneously, and the temperature increase rate was set to 2 °C/min.
Chapter 3

Aiming at understanding the behavior of the plastic strain and the failure criterion for concrete at high temperatures, high-temperature compressive stress tests with respect to plain concrete and concrete which is laterally confined with hoops (confined concrete) were performed for temperatures up to 800 ºC, where the compressive strength of the concrete made with andesite as the coarse aggregate was between 50 and 115 N/mm$^2$.

- The longitudinal and the lateral strain of the concrete increase together with its temperature, where the higher the strength, the higher the increase rate.
- As the temperature increases, the ratio of the lateral strain to the longitudinal strain also increases, and at 800ºC the magnitude of the lateral strain overtakes that of the longitudinal strain.
- From the behavior of the volumetric strain, it can be considered that the higher the strength of the concrete, the more pronounced the decrease in the creep failure stress.
- The dilatancy angle for the plastic flow rule as derived from the stress-strain relation at high temperatures increases in accordance with the stress ratio (stress/compressive strength at each temperature), and the angle larger for higher strengths.
- As the temperature increases, the dilatancy angle does not change considerably between ambient temperature and 200ºC. However, it increases between 200ºC and 600ºC and decreases between 600ºC and 800ºC.
- For practical amounts of lateral reinforcement, the failure criterion for concrete between ambient and high temperature takes a Drucker-Prager form which has been made dimensionless by dividing it by the compressive strength of plain concrete.
- The increase in strength due to lateral stress is higher for lower water-binder ratios, and it was found that the increase in compressive strength due to the confined effect is notable.
- The result of reproducing the confined experiment through finite element analysis using the derived plastic flow rule and the failure criterion yielded a relatively good match with the results for the increase in the compressive strength due to the hoop reinforcement. Furthermore, the stress-strain relation was also reproduced well, and it can be said that the derived plastic flow rule and the failure criterion are valid.

Chapter 4

Shrinkage strain (transient thermal strain) which is dependent on the stress is generated when concrete subjected to stress is exposed to heat. Measurements of the transient thermal strain were performed and the transient thermal strain was modeled for the purpose of elucidating the three-dimensional behavior of the strain in concrete.
exposed to heat in a state where compressive stress is applied at high temperatures. Furthermore, finite element analysis was performed for the purpose of determining whether the plastic flow rule derived in Chapter 3 is applicable to the flow rule of the abovementioned transient thermal strain, and as a result the following knowledge was obtained.

- The transient thermal strain per unit longitudinal stress is influenced by the water-binder ratio, whereby the lower the water-binder ratio, the lower the strain.
- If the water-binder ratio is above 30 %, the dilatancy angle of the plastic flow rule obtained from the high-temperature compressive stress test can be applied to the dilatancy angle of the flow rule of the transient thermal strain. In the case of water-binder ratio of 22.5%, the dilatancy angle of the plastic flow rule obtained from the high-temperature compressive stress test can be applied to the dilatancy angle of the flow rule of the transient thermal strain only if the stress level (operating stress/compressive strength at ambient temperature) is limited to 30% or less.

Chapter 5

The aim of this chapter was to confirm whether the material models obtained in Chapter 3 and Chapter 4 can be applied to reinforced concrete columnar members exhibiting a cross-sectional temperature gradient at times of fire, as well as to understand the cross-sectional stress distribution of the columnar members. Performing a thermal stress analysis and a subsequent comparison with the existing results, a discussion was provided regarding the changes in the stress distribution at times of fire, and the following knowledge was obtained.

- Since the longitudinal displacement for ultrahigh strength RC columns with andesite as the coarse aggregate as obtained from the results of fire resistance tests under loading match the analytical results, it is possible to predict the displacement behavior of RC columnar members using the material models from Chapter 3 and Chapter 4.
- When reinforced concrete columns are exposed to heat, the longitudinal and the lateral compressive stress increases due to thermal stress generated in the planar section of the heated surface at the onset of the heating, however, thermal stress is not generated in the corners.
- The fire resistance time increases together with the amount of hoop reinforcement. For practical amounts of hoop reinforcement, yielding of the hoop reinforcement occurs, and it can be predicted that the strength of the core concrete would eventually increase due to the confined effect.
6.3 Issues remaining to be solved

Several problems, outlined below, still remain to be solved after conducting the present research.

1) In the compressive test at 200°C, the displacement was extremely small, and as a result the lateral strain in the stress-strain relation could not be obtained as a smooth curve. There is a need to improve the measurement accuracy with respect to the lateral strain.

2) Since in the present study there was only one specimen for each experimental condition, it is necessary to gather more data by increasing the number of specimens.

3) Although the upper limit of the temperature was set to 800°C, the temperature of concrete structural members exceeds 800°C at times of fire. Therefore, it is necessary to understand the characteristics of concrete for even higher temperatures.

4) From the behavior of the volumetric strain at high temperatures, when stress exceeding half of the high-temperature compressive strength is applied for a long time, there is considerable chance that creep failures might occur. As the present research takes into account only the temperature dependency of the compressive stress, it is necessary to account for the time dependency as well and gather data related to the compressive stress under long-term heat exposure.

5) For water-binder ratio of 22.5%, if the compressive stress exceeds 40% of the compressive strength at ambient temperature, the flow rule for the plastic strain can not be applied to the transient thermal strain. Therefore, it is necessary to examine the flow rule for high stress by performing a separate set of tests.

6) Although the high-temperature characteristics of concrete are drastically influenced by the type of the coarse aggregate and the amount of the binder, there is no data for different types of concrete. Including the present study, there are only two studies related to the lateral strain at high temperatures. It is desirable to collect more data since concrete exposed to heat is in a state of multiaxial stress due to the emergence of thermal strain.