# Strength Development Properties of Core Specimens Taken from Structural Concrete Test Specimens Prepared All Over Japan

**Sachie Sato, Yoshihiro Masuda, and Hiroyuki Tanano**

## 1 Introduction

It is well known that concrete's strength development is affected by curing conditions such as temperature and moisture. In the field of building architecture in Japan, mix-proportion design and quality control protocols have long considered differences in compressive strength between structural concrete in members cast for use in real structures, and cylindrical specimens taken for quality control. Specifically, designers have assumed that a core specimen is similar in strength to a comparable specimen cured in water on site or seal-cured on site because of a similar temperature history, and therefore that its strength is the same as that of specimens cured on site. However, the wide variety of cement types, high strength requirements, and upsizing demands in recent concrete construction work means that this assumption becomes inaccurate for concrete structures made with various materials and conditions due to differences in temperature profiles and strength development as they harden.

This has prompted the adoption of a method in which the compressive strength of standard, water-cured specimens is compared with that of cylindrical, "core" samples taken from concrete specimens created to simulate structural members. The resulting data is used to guide mix-proportion designs and predict structural strength [1]. Also, derived correction factors for specific designs are given in a notification of the Ministry of Land, Infrastructure Transport and Tourism. When tasked with

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S. Sato (✉)
Department of Architecture, Tokyo City University, 1-28-1 Tamazutsumi, Setagaya, Tokyo 158-0093, Japan
e-mail: s-sato@tcu.ac.jp

Y. Masuda
Utsunomiya University, Utsunomiya, Tochigi, Japan

H. Tanano
Building Research Institute, Tsukuba, Ibaraki, Japan

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revising this bulletin, the authors previously proposed strength correction factors following an analysis of empirical data for structural concrete collected from many sources [2].

In this study, experimental data for concrete test members fabricated and tested at ready-mixed concrete plants all over Japan were collected and compared to examine the influence of temperature conditions and various other factors on the strength development of core specimens cut from the members.

## 2 Outline of Experiment

Almost all types of high-strength concrete do not conform to JIS. Therefore, before a proposed high-strength concrete can be applied in construction work, it must receive the approval of the Minister of Land, Infrastructure Transport and Tourism as a designated concrete construction material, as stipulated in Article 37-2 of the Building Standards Act.

In this study, surveyed data was collected from experiments performed to gain this approval between 2000 and 2004. Table 1 shows the survey's scope. Concretes made from three types of cement were considered—ordinary, moderate-heat, and low-heat Portland cement—all of which are standard products provided for in JIS R 5210—Portland Cement. Cements were manufactured domestically in all cases, by 10, 7, and 6 producers respectively.

Experiments followed the publication JASS 5 T-605 (Estimation procedure for structural concrete strength using core specimens). Specifically, the center of a concrete pillar is simulated by sandwiching a cubic concrete block (~1 $m^3$) between two layers of insulation foam at its top and bottom to prevent vertical heat propagation. Cylindrical "core" samples are taken from the block at designated time points. The temperature history (variation, maxima) inside the block is recorded starting immediately after the concrete is cast. For comparison, "standard-cured" cylindrical specimens are taken from the block during preparation, and undergo a standard underwater-curing procedure. Core and standard-cured specimens have their compressive strength measured and compared.

Figure 1 shows an overview of how these specimens are prepared and sampled.

In addition, specimens were classified according to the timing of their manufacture to account for seasonal variation in temperature conditions. Specifically, this framework was designed in the authors' previous work [3], based on distinct trends in the

**Table 1** Survey scope

| Cement type | Factories | W/C range(%) (C/W) |
|---|---|---|
| Ordinary | 391 | 23–60 (4.35–1.67) |
| Moderate-heat | 223 | 20–50 (5.00–2.00) |
| Low-heat | 143 | 20–48.5 (5.00–2.06) |

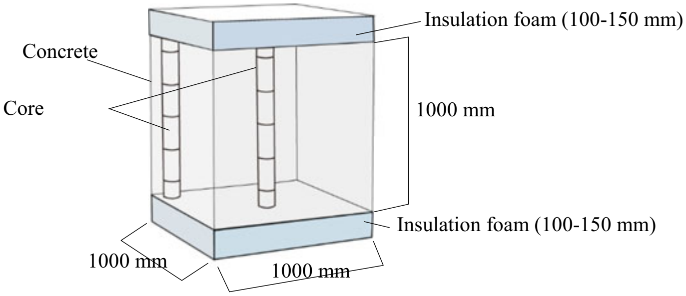

**Fig. 1** Model of concrete block specimen (JASS 5T-605)

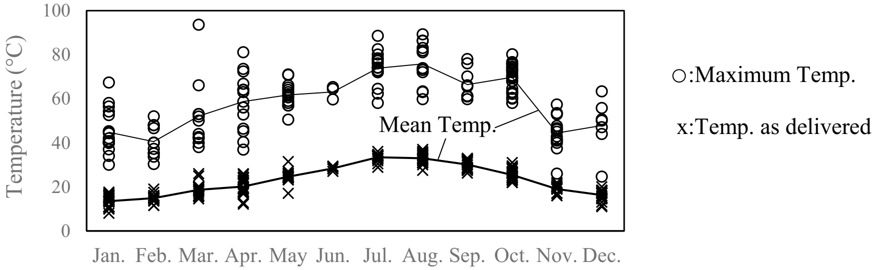

**Fig. 2** Delivery and maximum temperatures of concrete block specimens [3]

delivery temperature and maximum temperature of ready-mixed concrete members at construction sites: Standard (Spring/Fall), Apr-Jun, Oct-Nov; Summer, Jul-Sep; Winter: Dec–Mar (Fig. 2).

# 3 Results and Discussion

## 3.1 Cement-to-Water Ratio and Compressive Strength

Figure 3 shows the relationships of cement-to-water ratio (C/W) and compressive strength at 28 days for standard-cured specimens of ordinary, moderate-heat, and low-heat Portland cement, along with corresponding regression equations. Figure 4 shows the relationships of cement-to-water ratio and compressive strength for respective core specimens. Table 2 details the regression equation variables (slope, intercept) and standard errors for the relationships in Figs. 3 and 4 separately for the standard, summer, and winter conditions. Figure 3 and Table 2 indicate that the same cement-to-water ratio will result in the highest compressive strength for low-heat Portland cements, followed in descending order by moderate and ordinary types. In addition, the slope of this relationship is about 5–9% smaller for core specimens than

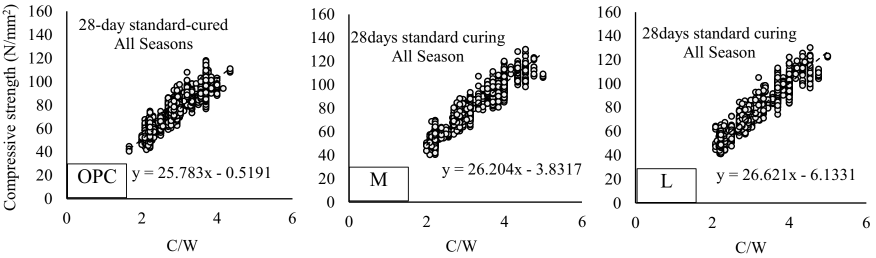

**Fig. 3** Relationship of cement-to-water ratio and compressive strength (standard-cured specimens)

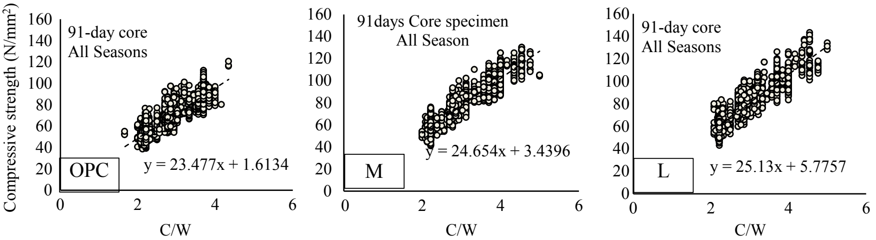

**Fig. 4** Relationship of cement-to-water ratio and compressive strength (core specimens)

standard-cured specimens. Standard errors range from 5 to 8 N/mm$^2$. Thus, mixture proportions should be designed with a cement-to-water ratio no smaller than the lower confidence limit indicated by these figures, so that the resulting concrete's strength does not drop below the target value. Practically, it is thought that low-heat portland cement is used for higher strength concrete.

### 3.2 *Relationship of Standard-Cured Strength and Core Strength*

Figure 5 shows the relationships of standard-cured strength and core strength for each type of cement. Core strengths of ordinary Portland cement at 28 and 91 days were respectively ~85 and ~94% of the standard-cured strength at 28 days. For moderate-heat and low-heat Portland cement, the core strengths at 91 days were respectively ~103 and ~109% of the standard-cured strength at 28 days. These data demonstrate that the strength development of core specimens differs from that of standard-cured specimens: lower heats of hydration during the curing period result in superior strength development. Similar experimental protocols will need to be vigilant for adverse effects if a core specimen exhibits a high temperature history during curing.

**Table 2** Results of regression analysis

| Cement | Season | 28-day standard-cured specimens | | | | 91-day core specimens | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Slope | Intercept | SE | N | Slope | Intercept | SE | N |
| OPC | All | 25.78 | −0.52 | 5.05 | 3107 | 23.48 | 1.61 | 6.64 | 3037 |
| | Spring/fall | 25.78 | −0.32 | 5.59 | 1110 | 23.46 | 2.02 | 6.25 | 1081 |
| | Summer | 25.81 | −1.51 | 5.12 | 1068 | 23.86 | −2.35 | 5.60 | 1047 |
| | Winter | 25.76 | 0.34 | 5.68 | 929 | 23.10 | 5.57 | 6.86 | 909 |
| Moderate | All | 26.20 | −3.83 | 5.43 | 1891 | 24.65 | 3.44 | 6.23 | 1885 |
| | Spring/fall | 25.99 | −3.27 | 5.25 | 621 | 24.36 | 4.34 | 6.20 | 618 |
| | Summer | 26.29 | −4.72 | 5.28 | 617 | 24.99 | 2.31 | 5.75 | 614 |
| | Winter | 26.31 | −3.49 | 5.65 | 653 | 24.61 | 3.66 | 6.68 | 653 |
| Low-heat | All | 26.62 | −6.13 | 6.07 | 1436 | 25.13 | 5.78 | 7.99 | 1390 |
| | Spring/fall | 26.27 | −6.32 | 6.29 | 475 | 24.91 | 6.61 | 8.03 | 459 |
| | Summer | 26.47 | −6.42 | 5.56 | 465 | 24.94 | 6.80 | 7.94 | 452 |
| | Winter | 26.71 | −5.70 | 6.25 | 496 | 25.50 | 4.08 | 8.02 | 479 |

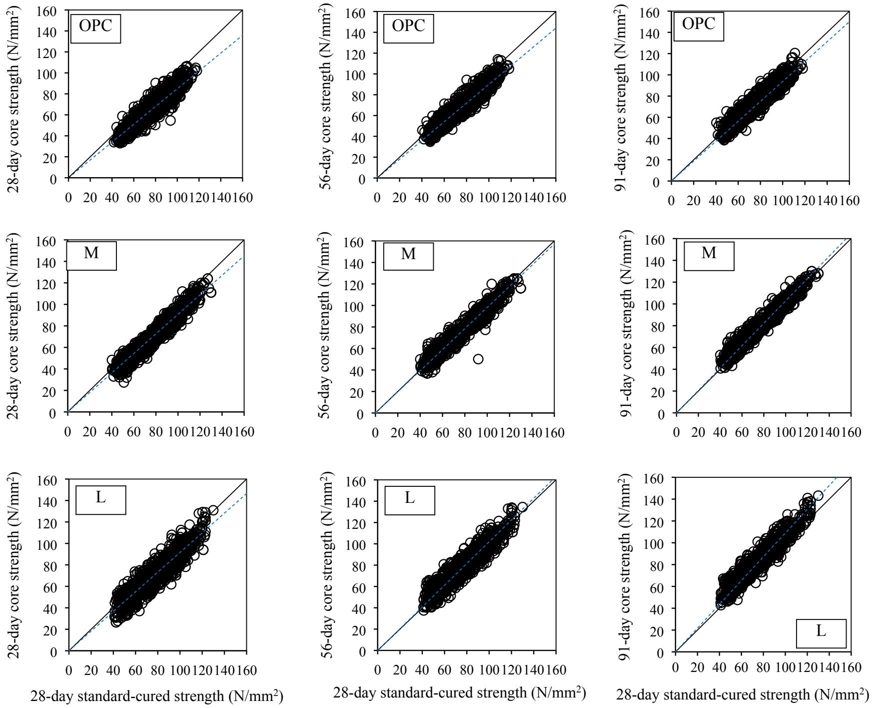

**Fig. 5** Relationship of standard cured strength and core strength

### 3.3 *Relationship of Maximum Temperature and Strength Development*

Figure 6 shows the relationships of maximum temperature and strength development ratio from 28 to 91 days for core specimens. Strength ratio falls with increasing maximum temperature for all types of cement, but this effect was weakest for ordinary cement. Thus, lower heats of hydration are associated with strength development at

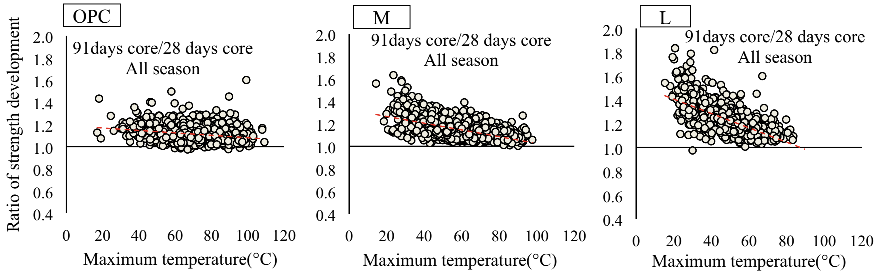

**Fig. 6** Relationship of maximum temperature and strength development ratio

28 days of curing being more susceptible to internal temperature history. Generally, concrete's strength development depends on the type of cement utilized. The maximum internal temperature of a member is reached around 24 h after casting: the higher this is, the more the material's strength is enhanced early in the curing process, which results in a 'plateauing' of the subsequent long-term strength increase. In addition, the effects of maximum temperature were most striking for low-heat Portland cement.

## 4 Conclusion

This study looked at experimental data for concrete specimens tested since 2000, exploring the relationships between cement-to-water ratio, standard-cured and core specimen strengths, and maximum curing temperature. As the results, the difference of strength development of core specimen by cement types was shown. Also, the strength development of low-heat Portland cement concrete was most affected by maximum temperature.

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