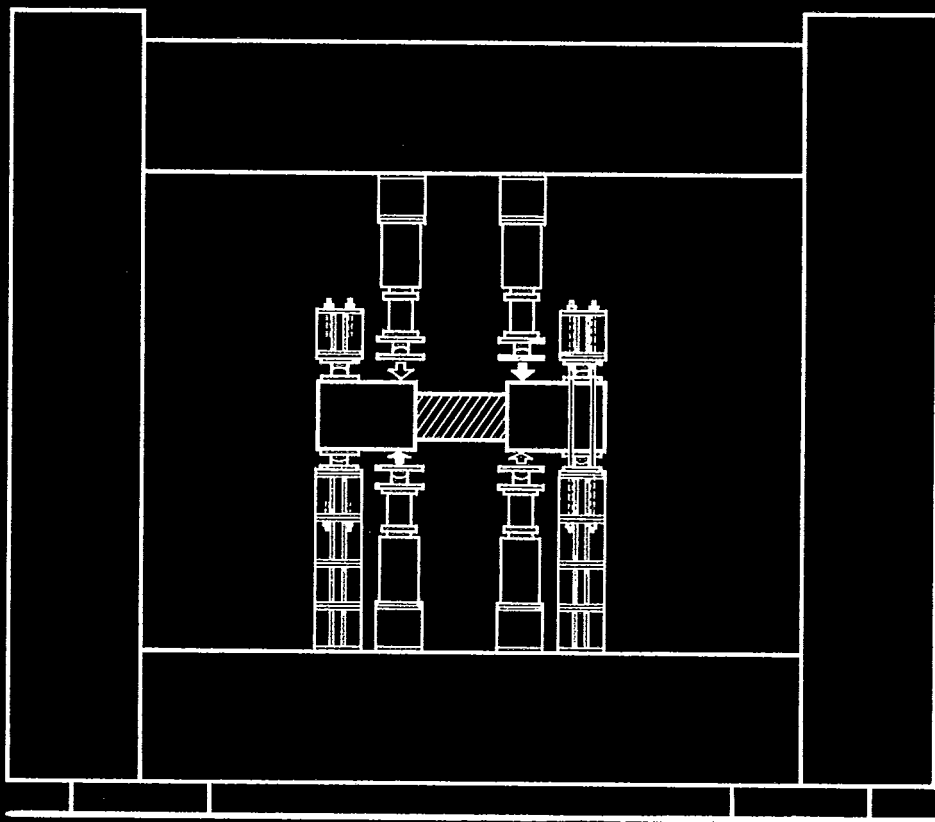


High-Strength Concrete

Second International Symposium

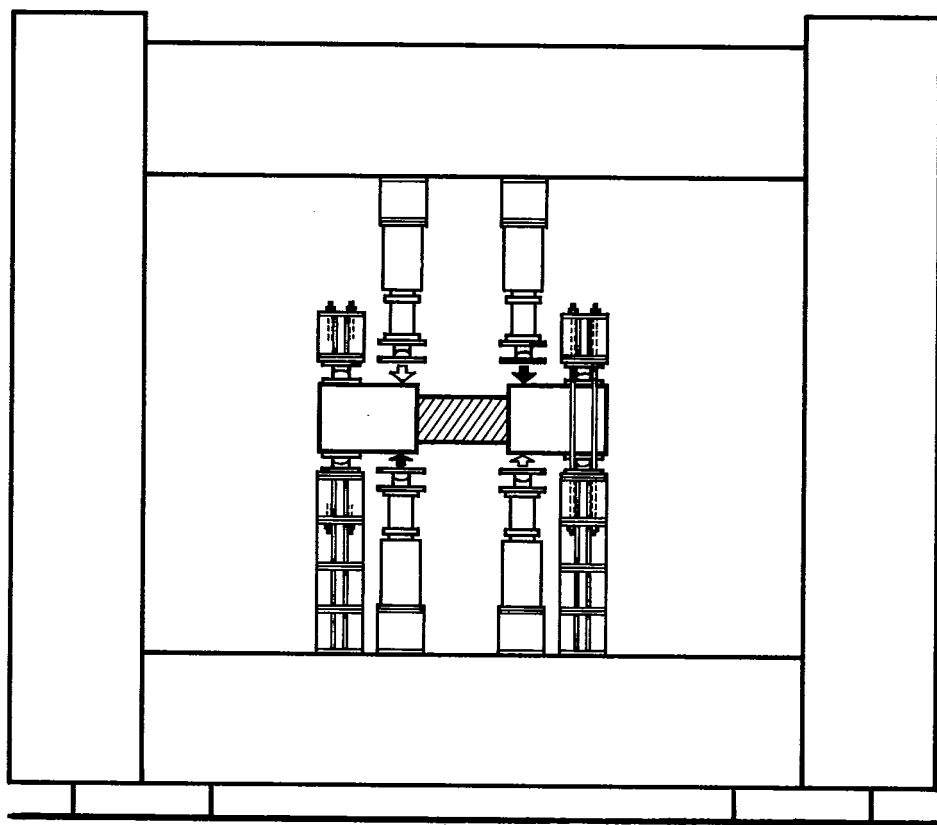


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High-Strength Concrete

Second International Symposium



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PREFACE

All of us interested in high strength concrete are indebted to the organizers and sponsors of the First International Symposium on Utilization of High Strength Concrete held in Stavanger, Norway, June 15 to 18, 1987. Experts in high strength concrete from throughout the world came together to discuss engineering developments and utilization of high strength concrete. Ideas and applications discussed during this meeting were widely reported and served as the basis for even greater utilization of high strength concrete in the future. This first symposium was sponsored by the Norwegian Concrete Association, the Norwegian Society of Chartered Engineers, the Federation Internationale de la Precontrainte (FIP), and The Norwegian Institute of Technology, Cement and Concrete Research Institute.

The Second International Symposium on Utilization of High Strength Concrete was held in Berkeley, California, U.S.A., May, 1990. A substantial amount of research work and project construction with high strength concrete was completed in the period between the two symposiums, and many recent findings were presented and discussed at this most recent meeting. We are particularly pleased with the breadth of discussion, ranging from structural design issues to materials selection, construction methods, and repair techniques.

The participants were surveyed to identify areas of consensus and areas where additional research is needed. There is a clear consensus that high strength concrete is exceptionally durable and readily obtainable in commercial practice. Use of silica fume, blast furnace slag cement, and other mineral and chemical admixtures can be particularly helpful in achieving the desired properties for the concrete. But, appropriate test methods need to be developed and we need a better understanding of in situ mechanical properties and overall structural ductility.

The Second International Symposium was co-sponsored by the University of California, Berkeley, California, U.S.A.; the American Concrete Institute (ACI), Detroit, Michigan, U.S.A.; the Precast/Prestressed Concrete Institute, (PCI), Chicago, Illinois, U.S.A.; and Canada Centre for Mineral and Energy Technology (CANMET), Ottawa, Canada.

This volume is a collection of the papers presented at the Second International Symposium. More than 50 papers were received from throughout the world and reviewed in accordance with American Concrete Institute policies. The cooperation of authors in preparation of their manuscripts, patient consideration of referee comments, and careful revision of their manuscripts is greatly appreciated. To those authors whose submissions could not be included in the symposium, the organizing committee extends its strong appreciation for their interest and hard work.

Weston T. Hester
Editor and Program Chairman
Berkeley, California

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Shortening of High-Strength Concrete Members

by H. G. Russell

Synopsis: When high-strength concretes are used in high-rise buildings, long-span bridges, and offshore structures, special attention must be given to the dimensional changes that occur in the concrete members. For design purposes, the length changes are usually considered to consist of instantaneous shortening, shrinkage, and creep. Instantaneous shortening depends on stress level, cross-sectional dimensions of the member, and modulus of elasticity of steel and concrete at the age when the load is applied. Shrinkage deformations generally depend on type and proportions of concrete materials, quantity of water in the mix, size of member, amount of reinforcement and environmental conditions. Creep deformations depend on concrete stress, size of member, amount of reinforcement, creep properties of concrete at different ages and environmental conditions. In recent years, questions have been raised about the validity of methods for calculating deformations in high-strength concrete members and about the in-place properties of high-strength concrete members. These properties include compressive strength, modulus of elasticity, shrinkage, and creep. This paper reviews existing state-of-the-art concerning instantaneous shortening, shrinkage, and creep of high-strength concrete members.

Keywords: beams (supports); columns (supports); compressive strength; creep properties; deformation; high-strength concretes; modulus of elasticity; shrinkage; strains

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INTRODUCTION

All concrete members change in length due to the effects of load and shrinkage. When differential shortening of members occurs, such as in high-rise buildings, the serviceability of the structure can be impaired. For structures built in the 1950's and designed by the working stress method, the effects of movements due to creep and shrinkage were secondary and could generally be neglected in design. However, with the utilization of higher strength concretes, the designer now has to consider how the length changes will affect the performance of the building. When appropriate, the effects have to be taken into account in design.

Column length changes within a single story height of a building may only be a fraction of an inch. However, over the height of a high-rise building, the length changes can amount to several inches. For example, a concrete building designed to be 1,000 ft (305 m) tall could shorten by 1 ft (0.3 m) due to gravity loads and shrinkage. The shortening of columns must be taken into account when detailing adjacent elements of the building that do not shorten that much. These elements include exterior partitions, interior partitions, elevator rails, and steel pipes. Differential movements between columns and walls within the building can result in sloping floor slabs unless the formwork for the floor slabs is set to accommodate future differential movements. In both cases, it is necessary to calculate the amount of differential shortening that is likely to occur. Differential vertical shortening can also result in serviceability problems where a high-rise building is connected to a low-rise building and adequate provisions have not been made for differential movements.

For calculation purposes, time-dependent deformations may be considered to consist of instantaneous deformations, creep deformations, and shrinkage deformations. In general, these deformations are assumed to occur independently, and the method of superposition is applied to determine the total length change. This assumption is not

completely correct in that shrinkage and creep deformations generally result in a reduction of stress in the concrete and an increase of stress in the reinforcing steel. However, with the current state of the art, consideration of this refinement from a design viewpoint is probably not warranted. Consequently, consideration of the effects separately is generally the approach taken by designers.

In recent years, questions have been raised about the validity of the method currently being used for the calculation of deformations in high-strength concrete members. Many of the factors taken into account when determining length changes have been determined for lower strength concretes but not for higher strength concretes. Consequently, it is only natural that the applicability of these procedures and properties to higher strength concretes should be questioned. The purpose of this paper is to review the existing state-of-the-art concerning instantaneous shortening, shrinkage, and creep of high-strength concrete members relative to North American design procedures and known material properties.

INSTANTANEOUS SHORTENING

Instantaneous deformations occur whenever load is applied to a concrete member. The deformation for any load increment may be calculated using the appropriate member stiffness for the concrete at the age when the load is applied. The total instantaneous deformation at any age is then the sum of the incremental deformations up to that age. The number of increments used in the calculations will vary depending on the number of stages of construction and the age of the concrete.

For example, a small load will generally come onto the columns within a few days of casting. This load can vary from the self weight of the next column to the weight of a full bay of dead load plus construction loads. The amount and timing of these loads will vary depending on the type of falsework used. The maximum load will not come onto the column until the building is completed and occupied. For lower columns in a high-rise building, this will be many months after the column is cast. For most stories of a high-rise building, the largest proportion of instantaneous deformation is caused by dead load of the columns, walls, and floors. Very little instantaneous deformation is caused by live load.

The instantaneous strain ϵ_I in a member caused by an incremental axial load P is given by:

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$$\epsilon_I = \frac{P}{A_C E_C + A_S E_S} \quad (1)$$

where

A_C and A_S = area of concrete and steel, respectively.

E_C and E_S = modulus of elasticity of concrete and steel, respectively, at age when load P is applied.

For a given member, the areas of concrete and steel are defined and modulus of elasticity of the steel is known. The only variable with time is the modulus of elasticity of the concrete. Traditionally, the modulus of elasticity of the concrete has been calculated using the following equation from the ACI 318 Building Code(1) modified to use compressive strength of concrete at age of loading:

$$E_C = w_C^{1.533} \sqrt{f'_{ca}} \quad (2)$$

where

w_C = unit weight of concrete

f'_{ca} = compressive strength of concrete at age of loading

Using the assumptions that stress is proportional to strain, plane sections remain plane, and strain in the steel is equal to strain in the adjacent concrete, Equation 1 has a sound theoretical basis. It has been shown to be valid experimentally for lower concrete strengths.(2) Experimental verification of the applicability of the equation for reinforced concrete members with concrete compressive strengths above 10,000 psi (69 MPa) needs to be verified. However, it is the author's opinion that the equation can still be used because of its theoretical derivation.

Considerable controversy surrounds the use of Equation 2 from two aspects. Equation 2 was developed by Pauw(3) on the basis of concrete with compressive strengths up to about 5500 psi (38 MPa). As additional data have become available on higher strength concretes, various investigators have made comparisons between the equation and the data for higher strength concretes. Figure 1 represents a compilation of data published by Nilson.(4) Based on these data, a modified equation was recommended for the calculation of the modulus of elasticity. This revised equation predicted a lower modulus of elasticity for higher strength concretes than the

values obtained using Equation 2. However, more recent data published by Cook(5) and shown in Fig. 2 indicate that Equation 2 underestimates the modulus of elasticity for the higher strength concretes. It should be noted that the higher strength concretes reported by Nilson were obtained using a smaller aggregate size. However, Cook was able to produce higher strength concretes using larger size aggregates.

It should be recognized that Equation 2 was based on a statistical analysis of the available data. As such, there is considerable scatter in the relationship between modulus of elasticity and concrete compressive strength. Consequently, it is recommended that, when accurate calculations are required for high-strength concretes, the modulus of elasticity should be measured as part of the concrete mix design preparation. Alternatively, the engineer must assume that there is going to be some deviation from the values predicted by Equation 2 or any other selected equation.

The second controversial item surrounding the calculation of instantaneous deformations is a question as to whether the modulus of elasticity as measured on a 6x12-in. (152x305 mm) concrete cylinder or other plain concrete specimen is applicable to large size structural members. Currently, there are no published data on this topic related to high-strength concrete. However, Hester and Cook have extracted cores from large concrete members and measured their modulus of elasticity. For the strength levels used in his program, Cook showed that the modulus of elasticity as measured on cores varied as the measured compressive strength varied. If the core strength was low, the modulus of elasticity was also low. Hester also observed the same phenomena. However, both strengths and modulus of elasticity of cores were lower than corresponding values measured on cylinders. This implies that actual deformations in full size structures may be larger than calculated.

CREEP

Creep deformations in a member depend on creep properties of concrete at age of loading, stress level in the concrete, size of member, amount of reinforcement and environmental conditions. The creep properties of unreinforced 6x12-in. (152x305 mm) concrete cylinders obtained from various concretes used in Water Tower Place,(6) Chicago, are illustrated in Fig. 3. In addition, Fig. 3 includes the creep properties of 14,000 psi (97 MPa) concrete used in some experimental columns at Chicago

Mercantile Exchange. The data are presented in terms of creep per unit stress. As can be seen from Fig. 3, the creep deformation of plain concrete varies depending on the age when the load is applied. It is also evident that the creep per unit stress of higher strength concretes is less than the creep per unit stress of lower strength concretes. Fintel, et al(7) have suggested that creep per unit stress varies from $0.003/f'_c$ to $0.005/f'_c$ where f'_c is the compressive strength of concrete at 28 days.

It should be recognized that for a given concrete strength, the creep will be different for different materials. The data shown in Fig. 3 are plotted in terms of creep per unit stress. For concrete stress levels less than 40% of the concrete compressive strength, it is generally considered that the total creep deformation is proportional to the stress level. This has been established experimentally for lower strength concretes but not for high-strength concretes. However, the short-term stress-strain curve for high-strength concrete is more linear than the stress-strain curve for lower strength concretes. Consequently, it is likely that the linear relationship between creep deformation and stress is still valid for higher strength concretes and could even be valid above the 40% stress level.

Since the creep deformations of concrete vary with age of loading, calculations for creep deformations require an incremental analysis. The analysis must take into account that the load will not be applied to some members until many months after the columns are cast. This has the impact of significantly reducing the calculated and actual creep deformations.(8-10) To perform these calculations accurately, a knowledge of how much the creep decreases with age of loading is needed.

The total amount of creep and the rate of creep are influenced by the size of the member. Large members have less creep and will creep at a slower rate than smaller members. This factor has to be taken into account when extrapolating data measured from the creep on standard 6x12-in. (152x305 mm) cylinders.(11) For column sizes used in high-rise buildings, the creep of unreinforced columns could be approximately 60% of that occurring on 6x12-in. (152x305 mm) cylinders. It should be noted that most of the correction factors that are used to take into account size effect are based on the work by Hansen and Mattock.(11) The highest strength concrete used in their investigation had a compressive strength of about 6000 psi (41 MPa). Data by Ngab(12) obtained for higher compressive strength concretes suggest a different relationship.

Creep is also reduced by the presence of reinforcement. A column with 8% reinforcement will have considerably less creep than the same size column with 1% reinforcement but carrying the same stress level in the concrete. This has a big impact on the creep deformations in the lowest columns of a high-rise building. The lowest columns may have the maximum amount of reinforcement permitted by the building code. Correction procedures to take into account the effects of reinforcement have been developed by Dischinger(13-15) and used by Fintel(7,16), Pfeifer,(9) and Russell.(8,17) These procedures rely on the input of certain empirical data. The applicability of Dischinger equations to columns in buildings was demonstrated by Pfeifer.(2) Reasonably good agreement was obtained between measured and calculated deformations.

In calculating creep deformations in columns, it has been accepted that deformations may be calculated in a series of increments. The creep deformations from each increment are added using the theory of superposition. The validity of the superposition for higher strength concretes has not been verified.

Most available data on creep have been obtained from specimens stored and tested under standard laboratory conditions of temperature and humidity. Data on lower strength concretes indicate that creep is influenced by both temperature and humidity. It is likely that the same effect will apply to high-strength concretes. However, data are not available to illustrate the magnitude of the effect. The situation is further complicated when consideration is given to the fluctuations of outdoor environment and that a column may undergo a large change in temperature before it is enclosed in the building.

SHRINKAGE

Shrinkage of concrete is generally determined on the basis of measurements of the length changes of 6x12-in. (152x305 mm) cylinders or similar specimens. In a structural member, the amount of shrinkage is influenced by the size of the member and the amount of reinforcement. Data obtained for different strength concretes used in Water Tower Place(17) are shown in Fig. 4. Generally, the shrinkage of 6x12-in. (152x305 mm) cylinders tends to be in the range of 600 to 900 millionths for most concretes.

When calculating the shrinkage deformation in structural members, the size of the member and the effects of reinforcement must be taken into account.

A large member will shrink at a slower rate than a small column(11) and for practical purposes will undergo less shrinkage. The size correction factors used for shrinkage are generally based on the work of Hansen and Mattock.(11) As mentioned above, their highest strength concrete had a compressive strength of about 6000 psi (41 MPa). The variation in calculated shrinkage due to size effects is much larger than the variation likely to occur as a result of changes in concrete constituents.

The effects of reinforcement on shrinkage have been demonstrated by Pfeifer.(2) Analytical procedures have been developed by Dischinger(13-15) and used by Fintel,(7,16) Pfeifer,(9) and Russell(8,17) for concretes with compressive strengths up to 9,000 psi.

Environmental conditions influence shrinkage in a similar manner to their effect on creep. It is well known that higher relative humidity results in less shrinkage of small specimens. However, the effect of relative humidity on the shrinkage of large members is unknown. It could even be assumed that large high-strength concrete members experience very little effect from changes in relative humidity due to the dense matrix.

ACCURACY OF PREDICTIONS

Total shortening of an individual concrete member may be determined by adding instantaneous, creep, and shrinkage deformations. In buildings, the total shortening may be used to determine required clearances between exterior wall panels, elevator rails, and rigid interior partitions. In long-span post-tensioned bridges, the deformations affect both prestress losses and camber changes.

Effects of column or bridge shortening are cumulative throughout the height or length of the structure. Shortening over 60 to 70 stories of a building can amount to many inches. Whereas total shortening in itself may not be a problem, differential shortening between different members requires particular attention. In a building, some of the differential is accommodated each time a new floor is cast. It is, therefore, only the differential movement that occurs after a particular level is constructed that is important for that level. Net differential movements may be determined by summing the vertical shortening at each level from the foundation to the level under consideration. Appropriate ways to accommodate the calculated differential movements can then be considered by the designer.

Deformation can be calculated to as many significant figures as the designer cares to specify. However, the accuracy of the numbers is only as good as the accuracy of material data used for the input and the proven accuracy of the prediction method. The objective of this section is to review the accuracy of predictions.

Variation of Material Properties

The previous sections on instantaneous shortening, creep, and shrinkage have recognized that concrete is a material whose properties are variable. Even when identical concretes are produced with no intended variations in the materials, the resultant properties will show some variation. The property that is likely to vary the least is the concrete compressive strength, yet it is not unusual to have variations of plus or minus two standard deviations. This in turn will result in variations in the modulus of elasticity of plus or minus one standard deviation on the assumption that Equation 2 provides perfect correlation. With this in mind, it is not unreasonable to expect that the modulus of elasticity would vary plus or minus 10% from a mean value. Also, the mean value may be different from that assumed in design.

It should also be recognized that concrete compressive strength is often specified as a minimum value. Consequently, actual strengths are higher than the minimum value. Calculations of instantaneous shortening should take into account whether the modulus of elasticity corresponds to the minimum compressive strength that is being used or one corresponding to the actual compressive strength. In the calculation of relative deformations, an underestimate of shortening can be as critical as an overestimate of shortening. Calculations should be made as a best estimate with recognition given to possible variations. It is, therefore, important that material properties be known as accurately as possible.

Accuracy of Prediction Methods

Within North America, two general methods are most frequently used to calculate shortening of concrete members. The methods are those of the European Concrete Committee(18) and the American Concrete Institute Committee 209(19). Both of these methods allow the designer to make a complete prediction of the time-dependent deformations with very limited information about the actual material properties.

The accuracy of these prediction methods can be considerably improved when material properties of the specific concretes to be used in a structure are known. For example, a measured modulus of elasticity would improve the accuracy compared to a value calculated using Equation 2. Similarly, creep and shrinkage data measured on standard specimens (20) provide a better starting point than creep and shrinkage calculated from the assumed concrete materials. In recent years, construction specifications for several long-span bridges have required the contractor to measure the creep and shrinkage properties of the concrete for comparison with the design assumptions. Although these were not high-strength concrete bridges, the importance of this approach with high-strength concrete members cannot be overstressed.

It must also be recognized that the prediction methods represent some average of the available data. As such, they cannot be expected to allow for the precise prediction with all different types of concrete.

Comparisons with Actual Shortening

Despite the inherent sources of inaccuracy described in the previous sections, comparisons of field measurements with actual shortening have shown a remarkable degree of accuracy. (7-9,17) One example of calculated shortening versus measured shortening for different levels in a building is shown in Fig. 5.(17) The curves marked "I" indicate the instantaneous shortening. The curves marked "I+S" represent the instantaneous shortening plus shrinkage. The curves marked "T" are the total shortening caused by instantaneous shortening, shrinkage, and creep. The contribution from instantaneous shortening, shrinkage, and creep varies for different levels. For the lower columns, instantaneous shortening provides the larger contribution to the total during construction. Thereafter, instantaneous deformations remain constant but shrinkage and creep continue to increase. At the higher levels in the structure, shrinkage and creep contribute a larger proportion. For example, at the top story of a building, shrinkage is the predominant effect causing shortening. This occurs because the columns at this level are only lightly loaded and contain minimum reinforcement. It should be noted that the highest strength concrete used in the building had a specified compressive strength of 9000 psi (62 MPa).

In the laboratory, it is possible to set up tests to measure the three components of instantaneous shortening, creep, and shrinkage. However, in an actual structure, the opportunity to separate these effects is generally not available. Consequently, we can only compare the total calculated deformations with the measured values. It is possible to achieve good correlations between total measured and calculated deformations but have the individual components incorrect with an overall cancelling effect of the errors. However, if sufficient comparisons are made and agreement obtained for a variety of member sizes, reinforcement percentages, loading histories, and concrete properties, it may be assumed that the method provides a reasonable tool for design. It should be recognized that correlations to date have been limited to concrete columns with design compressive strengths below 10,000 psi (69 MPa).

The designer must also realize that despite the precision with which the calculations can be made, the answer is only as accurate as the concrete properties used in the analysis. Furthermore, variations between the assumed design properties and those of the actual concrete used in the structure will lead to discrepancies. It is, therefore, important that a range of properties be considered and the effects determined. An example of this comparison is shown in Fig. 6(17) where curves 1, 2 and 3 are based on concretes with different assumed creep properties.

The rate of construction assumed in the design process is based on the designer's best assumption. The actual construction speed may be different from that assumption. Consequently, in situations where deformations are critical, it may be advisable to recalculate the deformations at several stages during construction based on the contractor's best estimate of construction speed and actual construction rate. With the availability of computer programs, additional calculations are easily made after the basic data are input.

CONCLUSIONS

With the greater utilization of high-strength concrete, questions have been raised about the applicability of existing design expressions for use in high-strength concrete members. This concern has arisen because much of the data for design considerations has been obtained on lower strength concretes. With regard to the shortening of high-strength concrete members, the key properties are

modulus of elasticity, shrinkage, and creep. The purpose of this paper has been to outline some of the knowledge that we have about the time-dependent shortening of high-strength concrete members.

The paper has emphasized the importance of utilizing realistic material properties and realistic construction schedules in making shortening predictions. It has also stressed that concrete is a variable material. We must recognize that these variables will have an effect on the actual shortening occurring in high-strength concrete members.

Despite the variations that exist in high-strength concrete and the lack of information about some of the properties, good correlation has been obtained between calculated and measured deformations on real structures. These correlations had been conducted for structural members with concrete compressive strengths up to 10,000 psi (69 MPa). There is currently a need to extend these types of correlations to members with higher concrete compressive strengths. Concrete with compressive strengths up to 20,000 psi (138 MPa) is currently available, yet we have very limited published data about the material and structural properties of these concretes. It is therefore important that industry pool its resources to develop this information as rapidly as possible.(21)

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REFERENCES

1. ACI Committee 318, Building Code Requirements for Reinforced Concrete, American Concrete Institute, Detroit, 1983.
2. Pfeifer, D. W., "Reinforced Lightweight Concrete Columns," Journal of the Structural Division, American Society of Civil Engineers, Vol. 95, No. ST1, January 1969, pp. 57-82.
3. Pauw, A., "Static Modulus of Elasticity of Concrete as Affected by Density," Journal of the American Concrete Institute, Proceedings Vol. 32, No. 6, December 1960, pp. 679-687.
4. ACI Committee 363, "State-of-the-Art Report on High-Strength Concrete," Journal of the American Concrete Institute, Vol. 81, No. 4, July-August 1984, pp. 364-411.
5. Cook, J. E., "Research and Application of High-Strength Concrete: 10,000 psi Concrete," Concrete International Design & Construction, American Concrete Institute, October 1989, Vol. 11, No. 10, pp. 67-75.
6. Russell, H. G., "High-Rise Concrete Buildings: Shrinkage, Creep, and Temperature Effects," Analysis and Design of High-Rise Concrete Buildings, Publication SP-97, American Concrete Institute, Detroit, 1986, pp. 125-137.
7. Fintel, M., Ghosh, S. K., and Iyengar, S. H., Column Shortening in Tall Structures - Prediction and Compensation, PCA Engineering Bulletin EB108D, Portland Cement Association, Skokie, Illinois, 1987, 34 pp.
8. Russell, H. G., and Corley, W. G., "Time-Dependent Behavior of Columns in Water Tower Place," Douglas McHenry International Symposium on Concrete and Concrete Structures, Publication SP-55, American Concrete Institute. Also reprinted as PCA Research and Development Bulletin RD052.01B, Portland Cement Association, Skokie, Illinois, 1977, 10 pp.
9. Pfeifer, D. W., Magura, D. D., Russell, H. G., and Corley, W. G., "Time-Dependent Deformations in a 70-Story Structure," Designing for Effects of Creep, Shrinkage and Temperature in Concrete Structures, Publication SP-27, American Concrete Institute, Detroit, Michigan, 1971, pp. 159-185.



14 Russell

10. Pfeifer, D. W., and Hognestad, E., "Incremental Loading of Reinforced Lightweight Concrete Columns," Final Report, Eighth Congress of the International Association for Bridge and Structural Engineering, New York, Sept. 1968, pp. 1055-1063.
11. Hansen, T. C., and Mattock, A. H., "Influence of Size and Shape of Member on the Shrinkage and Creep of Concrete," Journal of the American Concrete Institute, Proceedings V. 63, No. 2, February 1966, pp. 267-290. Also reprinted as PCA Development Department Bulletin D103, Portland Cement Association, Skokie, Illinois.
12. Ngab, A. S., Slate, F. O., and Nilson, A. H., "Microcracking and Time-Dependent Strains in High Strength Concrete," Journal of the American Concrete Institute, Vol. 78, No. 4, July/August 1981, pp. 262-268.
13. Dischinger, F., "Investigations on Resistance to Buckling, Elastic Deformation, and Creep of Concrete in Arch Bridges (Untersuchungen Ueber die Knicksicherheit, die Elastische Verformung und das Kriechen des Betons bei Bogenbruecken)," Der Bauingenieur (Berlin), V. 18, No. 39/40, Oct. 1937, pp. 595-621, and V. 20, No. 47/48, Dec. 1939.
14. Illston, John M.; Leonhardt, Fritz; Soboyejo, A. B. O.; Wang, Chen H.; and Authors, Discussion of "Time-Dependent Load Transfer in Reinforced Lightweight Concrete Columns" by Thomas A. Holm and Joseph Pistrang, Journal of the American Concrete Institute, Proceedings V. 64, No. 6, June 1967, pp. 1587-1592.
15. Leonhardt, Fritz, Prestressed Concrete Design and Construction, 2nd Edition, Wilhelm Ernst and Sohn, Berlin, 1964, 677 pp.
16. Fintel, M., and Khan, F. R., "Effects of Column Creep and Shrinkage in Tall Structures - Prediction of Inelastic Column Shortening," Journal of the American Concrete Institute, Proceedings V. 66, No. 12, December 1969, pp. 957-967.
17. Russell, H. G., and Larson, S. C., "Thirteen Years of Deformations in Water Tower Place," Structural Journal, American Concrete Institute, Vol. 86, No. 2, March-April 1989, pp. 182-191.

18. Structural Effects of Time-Dependent Behavior of Concrete, Bulletin D'Information, No. 80, Comité Européen du Béton (CEB), Paris, February 1972.
19. ACI Committee 209, Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures, (ACI 209R-82) (Reapproved 1986), American Concrete Institute, Detroit, 1982, 108 pp.
20. Standard Test Method for Creep of Concrete in Compression, ASTM C 512, American Society for Testing and Materials, Vol. 04.02, Philadelphia.
21. Fiorato, A. E., "PCA Research on High-Strength Concrete," Concrete International Design & Construction, Vol. 11, No. 4, April 1989, pp. 44-50.

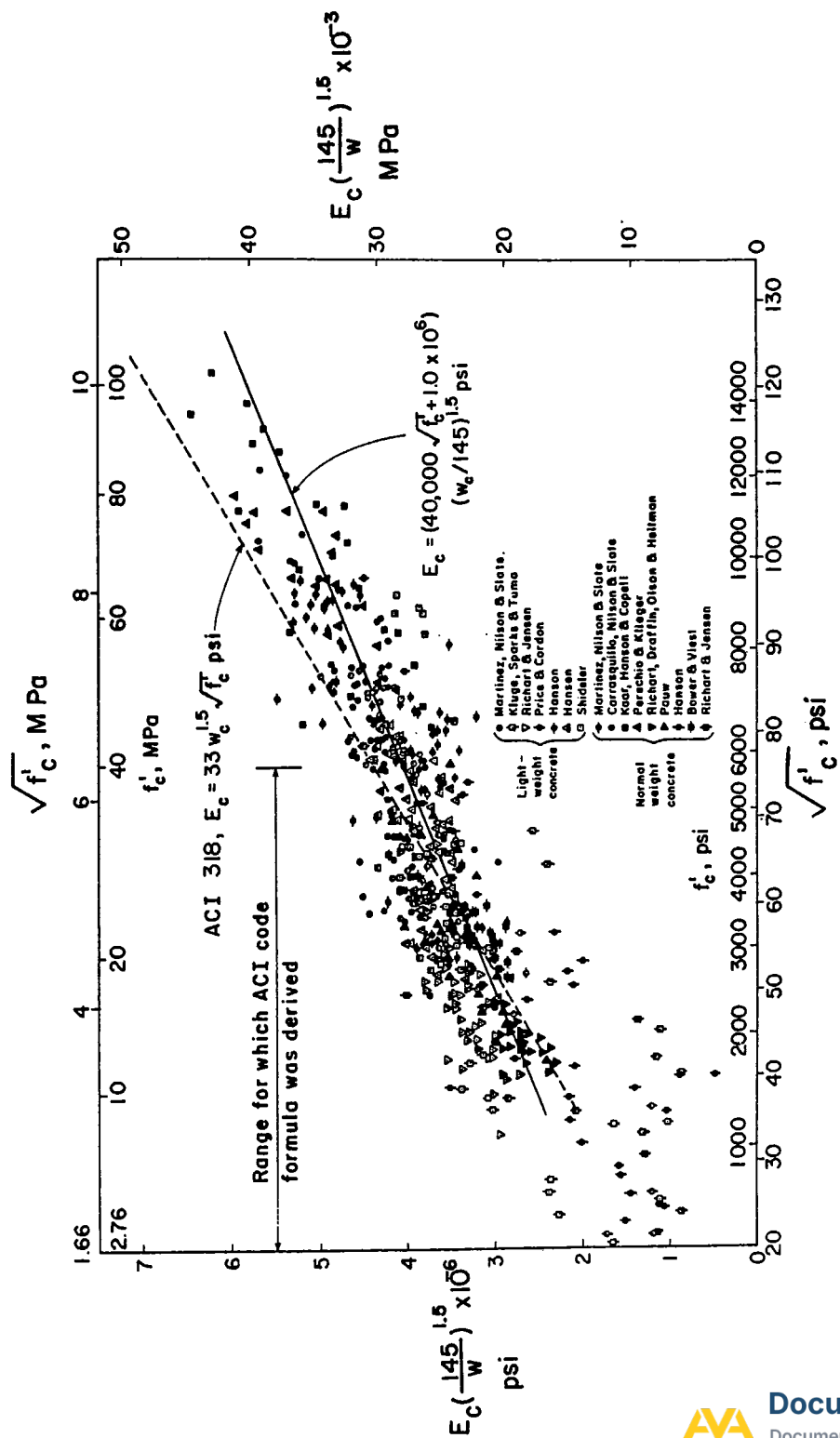


Fig. 1—Modulus of elasticity versus concrete strength reported by Nilsson (4)

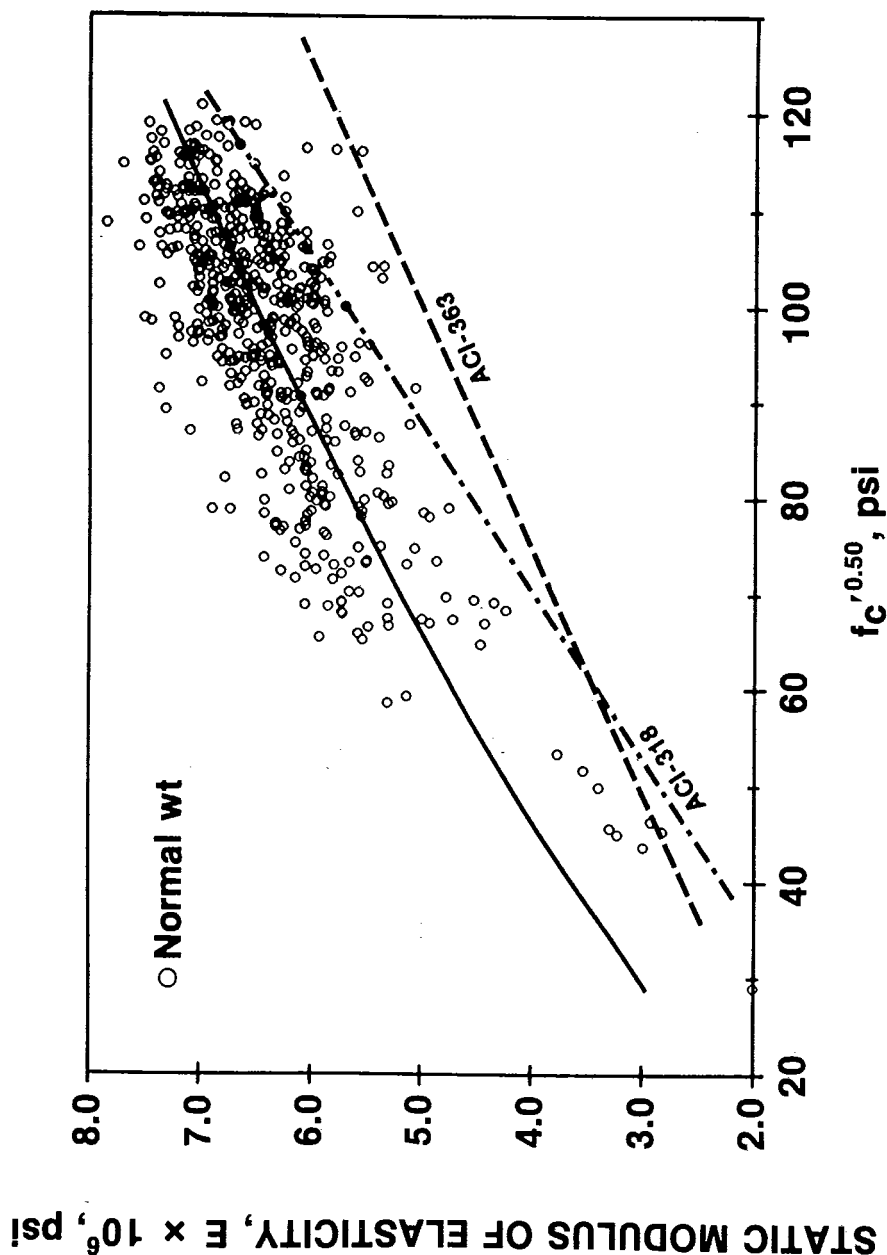


Fig. 2--Modulus of elasticity versus concrete strength reported by Cook (5)

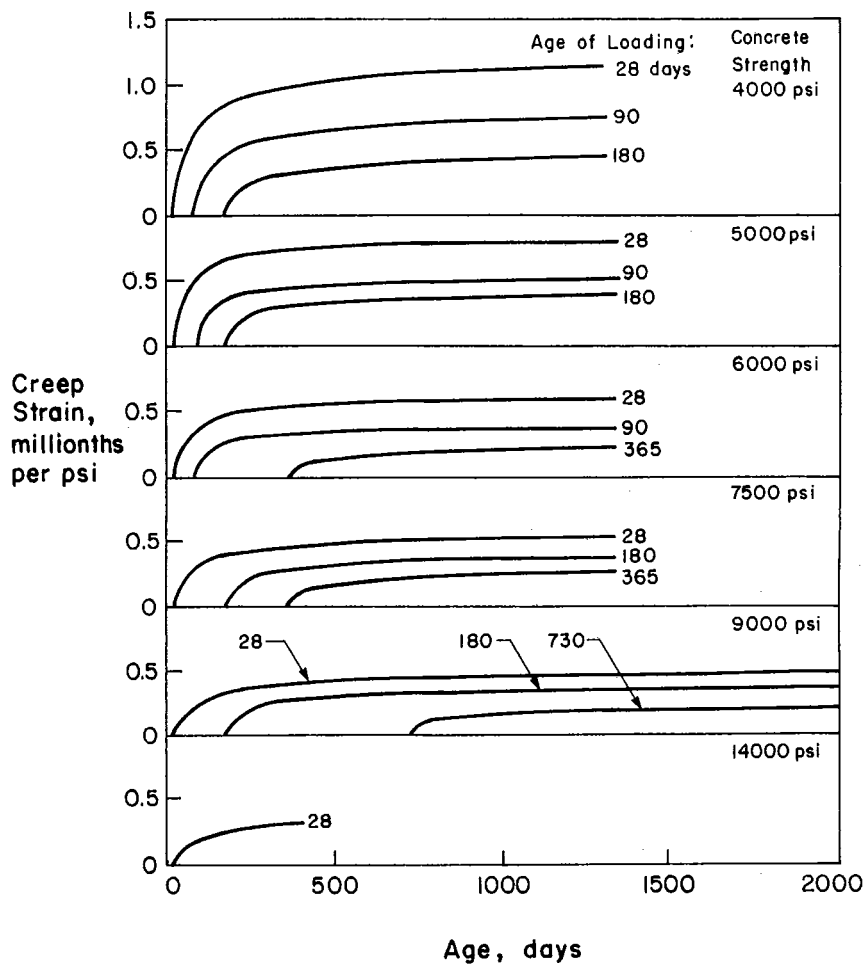


Fig. 3--Laboratory creep data(6)

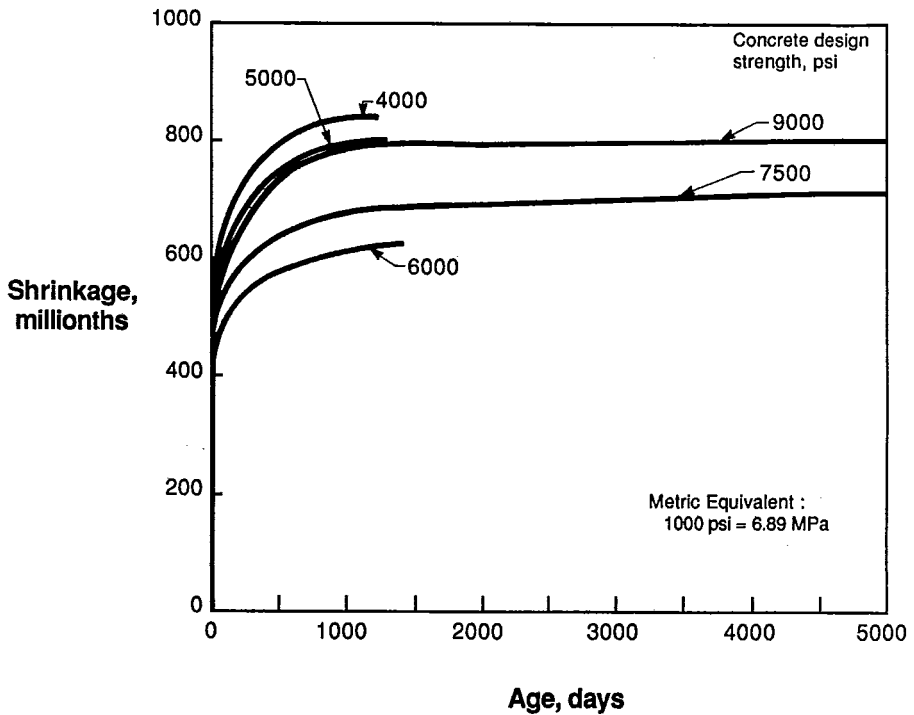


Fig. 4--Laboratory shrinkage data (17)

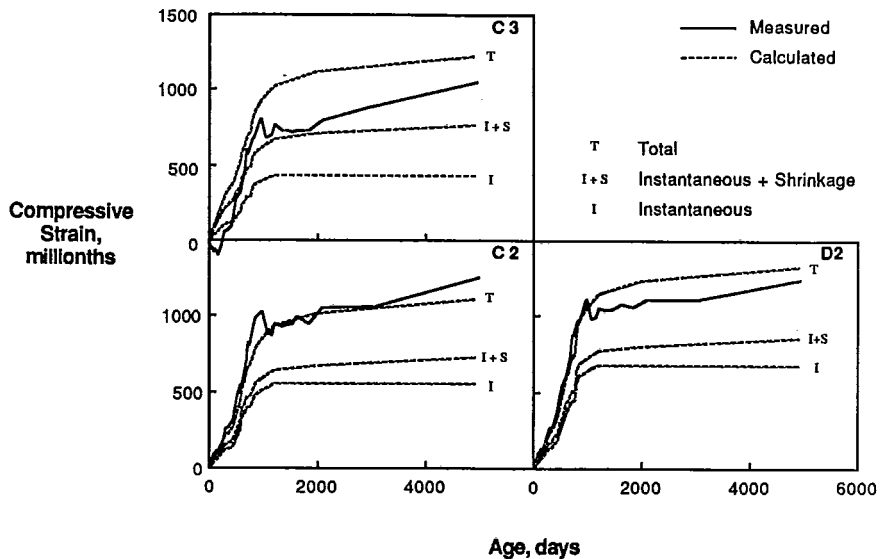


Fig. 5--Comparison of measured and calculated shortening for water tower place (17)

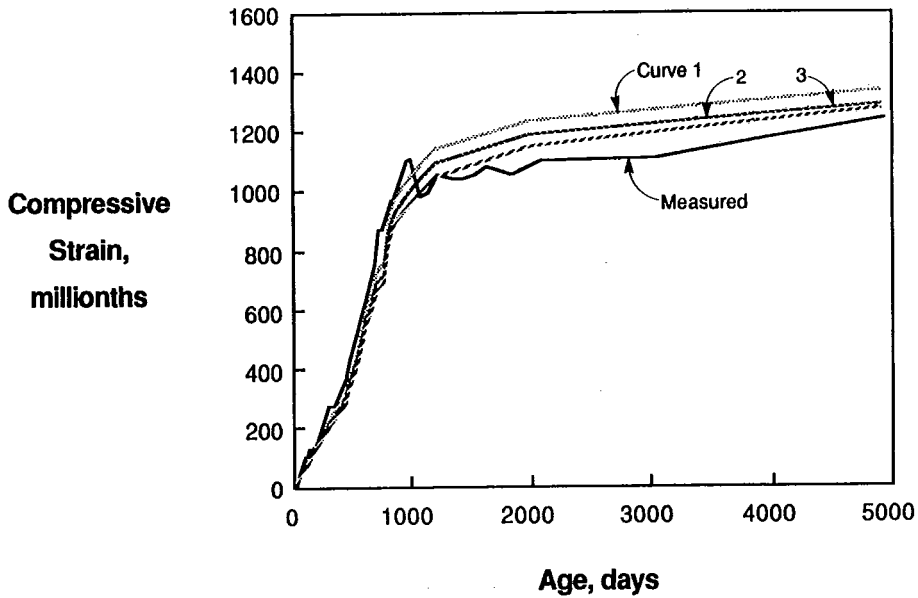


Fig. 6--Comparison of measured and calculated shortening for different concrete properties (17)

SP 121-2

Outline of the Japanese National Project on Advanced Reinforced Concrete Buildings with High-Strength and High-Quality Materials

by H. Aoyama, T. Murota,
H. Hiraishi, and S. Bessho

Synopsis: A National Project lasting five years has been promoted by the Ministry of Construction of Japan since 1988 to develop super highrise reinforced concrete buildings in seismic zones. The strength of concrete and reinforcing steel bars ranges from 30 to 120 MPa (4.3 to 17.4 ksi) and from 400 to 1,200 MPa (58 to 174 ksi), respectively.

The following will be investigated in the Project; a) production, quality control, and placement of high-strength concrete, b) production of high-strength steel bars, c) mechanical properties of high-strength concrete and steel bars, d) behavior of members and sub-assemblages, and e) structural design methodology.

Keywords: concrete construction; earthquake resistant structures; high-rise buildings; high-strength concretes; high-strength steels; quality control; reinforced concrete; research; structural design

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H. Hiraishi is Head of Structure Div., BRI. He is the manager of the New RC Project. His research activities are in the field of earthquake engineering and structural design of reinforced concrete buildings.

S. Bessho is Chief Research Engineer, Building Engineering Department, Kajima Institute of Construction Technology. He is a representative of construction companies involved in the New RC Project. His research activities are in the field of structural design and construction system of highrise reinforced concrete buildings.

INTRODUCTION

Recently, research and development related to reinforced concrete buildings using high-strength concrete has been actively promoted in Japan by private construction companies. Based on these activities, highrise RC buildings which have images remarkably different from those of ordinary RC buildings have begun to appear. Technology development on such a new field of RC building construction will continue in the future and the Ministry of Construction (MOC) will surely be requested to have technical standards for administration of such buildings, sooner or later.

Based on this background, the MOC decided to manage a five-year research project entitled "Development of Advanced Reinforced Concrete Buildings Using High-Strength Concrete and Reinforcement" (hereafter referred to as "New RC"). The New RC Project started in 1988 fiscal year with major objectives as follows:

- (1) To survey and analyze results of research and development conducted by private companies using a proper common measure and to establish a technology system for advanced reinforced concrete buildings (New RC buildings). If necessary, to execute basic researches for the systematization.
- (2) To understand the mechanical behavior of buildings made of high-strength concrete and reinforcing steel bars and to develop structural design systems suitable for New RC buildings.

Results of the project will be utilized as technical standards for the building administration and will encourage further research and development on advanced reinforced concrete buildings.

RANGE OF MATERIAL STRENGTH

Strengths of concrete and steel bars treated in the project ranges from 30 to 120 MPa (4.3 to 17.4 ksi) for concrete and from 400 to 1,200 MPa (58 to 174 ksi) for steel bars. In Fig. 1, major research fields in the project are shown on a plane where the vertical axis is the yield strength of steel bars and the horizontal axis is the compressive strength of concrete.

Small zones A and B in the figure surrounded by dotted lines correspond to the areas for current ordinary RC buildings and for highrise RC buildings, respectively, where the latter is about twenty through thirty stories high and is constructed under the Minister-of-Construction's agreement system specified in the Building Standard Law, Article 38.

Zones I, II-1, II-2 and III are zones treated in the project. They cover very large area compared to the two zones stated above. It is obviously unrealistic to assume that we can understand structural behavior of New RC buildings simply by extrapolating the knowledge on current reinforced concrete structures.

So, in the project, theoretical examination of experimental data on high-strength concrete structures will be emphasized to develop new technology systems. Current technical knowledge on reinforced concrete buildings will also be re-examined in the project.

In some zones far apart from the current reinforced concrete technology, basic problems will have to be examined and may not yield much practical results. Practical results are expected in Zones I and II-1, because these zones are comparatively close to the boundary of the current technology.

OBJECTIVES OF RESEARCH AND DEVELOPMENT AND FINAL EXPECTED RESULTS

The objectives of research and development and the corresponding final results expected in the project are summarized in Table 1. Some of the results will be applicable to refine the current reinforced concrete technology. Guidelines for the structural design or construction in the table will not give full details of technology but will give

basic principles for design and construction practice.

Guidelines of this type are preferred, because guidelines which define detailed technical specifications for structural design or construction often tend to impede development of relevant technology, and also future technical development will possibly change high-strength concrete technology so much as we can not predict.

RESEARCH ORGANIZATION

The Building Research Institute is in charge of conducting the project. Research committees are set up in Japan Institute for Construction Engineering (JICE) as shown in Fig. 2 to organize universities, private companies, etc.. Technical Coordinating Committee and Research Promoting Committee are assigned to determine research scheme, to coordinate research works, to promote the project and to integrate research results. These two committees and Technical Advisory Board is chaired by Aoyama.

Five technical committees are in charge of making research programs in detail, implementing research works and integrating research results in five particular fields. The chairmen of the technical committees are Prof. F. Tomosawa, University of Tokyo for Concrete Committee, Prof. S. Morita, Kyoto University for Reinforcement Committee, Prof. S. Otani, University of Tokyo for Structural Element Committee and Prof. T. Okada, University of Tokyo for Structural Design Committee. Construction and Manufacturing Committee will start in 1991.

Each of these technical committees has working groups as shown in Fig. 2.

ITEMS FOR RESEARCH AND DEVELOPMENT

Research items assigned to each technical committee are as follows:

Concrete Committee

- (1) Development of materials necessary for making high- and super high-strength concrete. Quality standards of the materials.
- (2) Physical properties of high-strength and super high-strength concrete.
- (3) Mix proportion design, casting and curing works and quality control.

Reinforcement Committee

- (1) Development of high-strength and super high-strength steel bars. Mechanical properties of steel bars.
- (2) Mechanical properties of confined concrete.
- (3) Constitutive equations for RC elements and application of finite element method.
- (4) Bond between concrete and steel bars. Anchorage and arrangement of steel bars.

Structural Element Committee

- (1) Mechanical properties of beams and columns.
- (2) Mechanical properties of shear walls.
- (3) Effect of shear force on beams, columns and shear walls.
- (4) Mechanical properties of beam-column joints and frames.
- (5) Mechanical properties of foundations.

Structural Design Committee

- (1) Methods for modeling and analysis of structural frames in each zone.
- (2) Practically feasible types of structural frames.
- (3) Design loads and requirements for structural performance.
- (4) Design methodology.

MAJOR RESEARCH TOPICS IN THE PROJECT

Major research topics in this research project will be as follows:

Ductility of high-strength reinforced concrete High-strength concrete has been used mainly as the countermeasure to high axial stress produced in the lower story columns of highrise buildings. Maximum number of stories of highrise buildings is almost completely determined by the concrete strength used in the structure. The highest RC building in Japan is now 25 stories for the specified strength of 36 MPa (5.2 ksi), and 30 stories for 42 MPa (6.1 ksi). From the viewpoint of axial stress, higher concrete strength will be the most vital element in order to realize higher buildings. High-strength concrete of 80 MPa (11 ksi) is already used in practice for prefabricated piles.

However, it has been pointed out that the falling branch of stress-strain curves of high-strength concrete is more pronounced (see Fig.3). It is very important to improve characteristics of core concrete by lateral confinement, and to evaluate the effect of the confining steel quantitatively. Also, a more elaborate supervision of construction work and of quality control will be required for the placement of high-strength concrete.

Research needs associated with high-strength steel bars Although super high-strength steel bars are used in practice

for shear reinforcement, further research is needed in establishing the method of structural evaluation of members with shear reinforcement of this kind. For longitudinal steel bars, the highest yield strength so far used in actual structures is 500 MPa. In order to use high-strength steel bars as longitudinal reinforcement, their quality should be improved because their tensile strain at fracture is fairly low as compared to that of ordinary steel bars (see Fig. 4).

Welding technique of high-strength steel bars and/or mechanical splices to join them together should also be developed.

Subjects regarding structural performance From the viewpoint of structural performance, following three subjects need to be investigated, in addition to the confinement of concrete and improvement of the quality of steel mentioned above.

(a) Bond between concrete and steel bars

The demand on bond between concrete and steel bars increases in proportion to the increase of yield strength of steel bars. On the other hand, the bond capacity does not increase in proportion to the increase of concrete strength. Thus the bond becomes one of the critical problems for the New RC structures. Particularly the resistance against bond splitting failure is an important subject for bar development and lap splices.

(b) Stiffness of members and structures

The use of high-strength steel bars in addition to high-strength concrete will result in a reduction of cross section. It causes stiffness decrease of members and structures. Also the stiffness of members becomes lower after cracking of concrete in proportion to the decrease in cross sectional area of longitudinal steel bars. Figure 5 shows test results of beams conducted by R. Tanaka(1). Therefore, careful consideration should be given to the stiffness as well as load carrying capacity and deformation capacity. Shear walls will be effective to increase stiffness of buildings.

(c) New structural design method

While various merits are expected in many specific items concerning high-strength materials, there are many problems to be solved as mentioned before. It is necessary to develop, not only technical measures to these problem, but also new structural design methodology considering the characteristics of high-strength materials.

CRITERIA FOR EARTHQUAKE RESISTANCE

Table 2 shows earthquake design criteria applied to the structural design of highrise buildings in Japan. These

criteria are not explicitly stipulated in the Building Code, but they are adopted for practical design in almost all cases by structural engineers, and thus form a kind of current consensus among engineers in Japan. These criteria will be applied to New RC buildings.

CONCLUDING REMARKS

The scope of research and development in New RC Project includes research fields far beyond frontiers of current knowledge on reinforced concrete structures. It is anticipated that we would encounter many difficulties in the course of the project.

Nevertheless, it is expected that our challenge to these difficulties would greatly enhance our knowledge to determine the future scope of reinforced concrete technology. This project has aroused prevalent interest in private companies, universities, and so on. Their cooperation and assistance will produce much fruit in this project.

One of the most important technologies in high-strength reinforced concrete buildings is the quality control of concrete. In Japanese structural design practice, the accuracy of quality control of concrete has never been reflected explicitly in the structural design. Attention will be paid in this project to the accuracy of quality control of concrete and its effect on the structural design.

REFERENCE

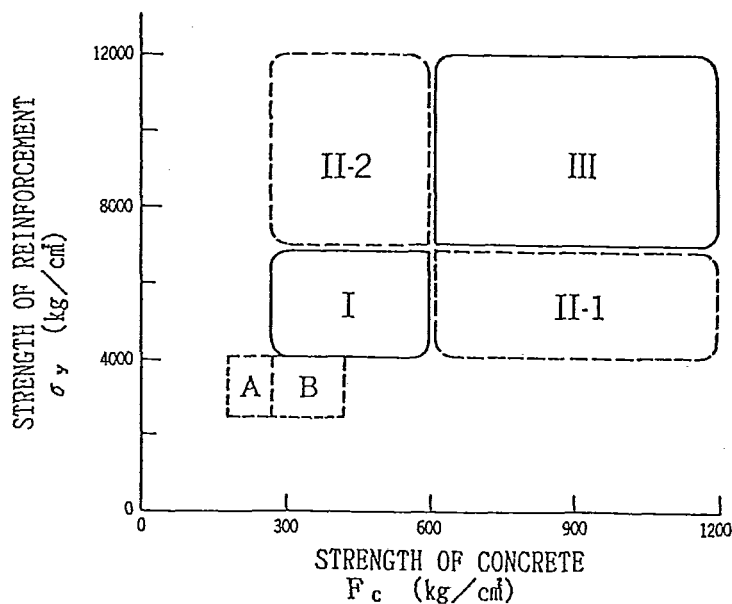
1. Tanaka, R. "For the Practical Use of High-Strength Steel Bars SD50," Quarterly Column, April 1987, Vol. 104, 91-97 (In Japanese).

Table 1 Objectives of research and development and final results expected

Objectives	Final Results Expected	
	For New RC	For Current RC
1) Development of high-strength and high-quality materials	• Methods for mix proportion method and quality control of concrete (Zone I) • Methods for production and arrangement of reinforcements (Zone I) • Guidelines for developing materials for Zone II and III	• Revision of design method for mix proportion and quality control method for concrete • Revision of reinforcement quality standards • Revision of upper limits of reinforcement strength
2) Evaluation of properties of structural members and frames	• Methods of analysis	• Revision of current methods of analysis
3) Development of design and construction guidelines	• Structural design guideline (Zone I) • Construction guideline (Zone I) • Draft guidelines for structural design and construction (Zone II, III)	• Revision of structural design methods • Revision of construction standards
4) Feasibility study on RC buildings in Zone II-1	• New type high-rise buildings	
5) Feasibility study on RC buildings in Zone III	• New images of RC buildings	

Table 2 Earthquake Resistant Design Criteria

Seismic hazard level	Level 1	Level 2
Probability of recurrence	Once in lifetime	Possible maximum
Maximum ground velocity	25 cm/s	40-50cm/s
Member force	Concrete cracks but no steel yields	Steel yields but no building collapses
Story ductility factor	less than 1	less than 2
Member ductility factor	less than 1	less than 4
Story sway angle	less than 1/200	less than 1/100



ZONE : TYPE OF RC BUILDINGS & MATERIALS

A: LOW-RISE BUILDINGS IN COMMON

B: HIGH-RISE BUILDINGS CONSTRUCTED IN LAST DECADE

I: HIGH-STRENGTH CONCRETE & REINFORCEMENT

II-1: ULTRA HIGH-STRENGTH CONCRETE & HIGH-STRENGTH REINFORCEMENT

II-2: HIGH-STRENGTH CONCRETE & ULTRA HIGH-STRENGTH REINFORCEMENT

III: ULTRA HIGH-STRENGTH CONCRETE & REINFORCEMENT

Fig.1 Strength of materials and fields of research and development

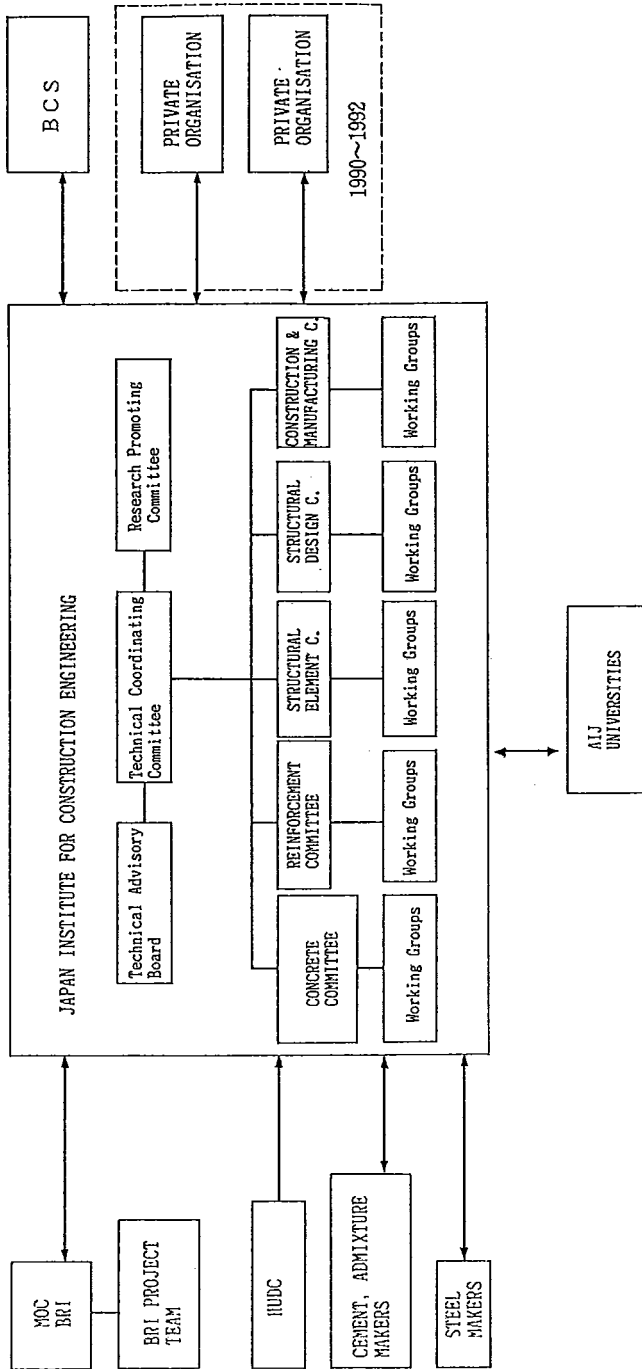


Fig.2 Organization for research and development

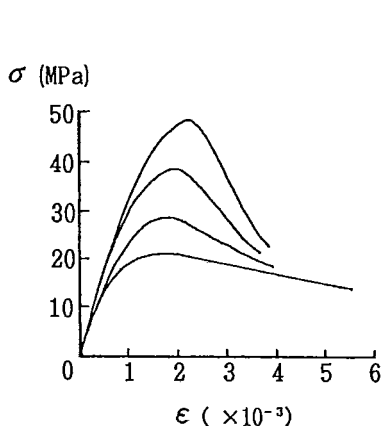


Fig.3 Idealized Stress versus Strain Relations of Concrete

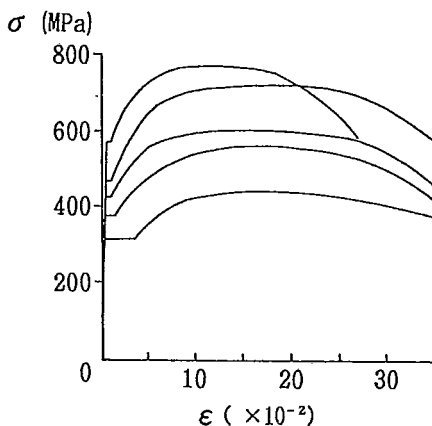


Fig.4 Stress versus Strain Relations of Steel Bars

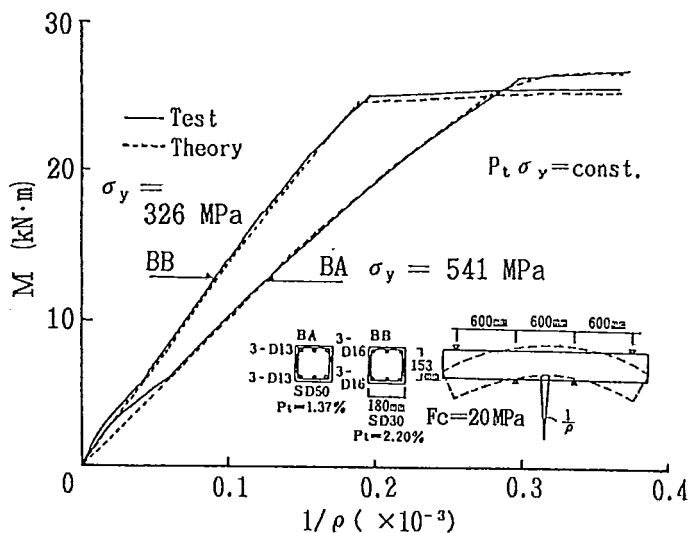


Fig.5 Bending Test of Beams with Deformed Bar of $\sigma_y = 326$ MPa and $\sigma_y = 541$ MPa

SP 121-3

High-Strength Concretes for High-Rise Buildings in Japan

by F. Tomosawa, Y. Masuda, M. Abe,
A. Shimizu, and S. Nakane

Synopsis: A Five Year National Research Project on advanced concrete buildings with high strength and high quality materials has been in progress in Japan since 1988. A High-Strength Concrete Committee was organized to establish guidelines which would be used in applying the high-strength concrete of 30 to 120 MPa to reinforced concrete buildings and has started to investigate the following items.

- a. Development of cements, aggregates, chemical admixtures, mineral admixtures for high-strength concrete and establishing of the quality standards of these materials and the design method of mix proportion.
- b. Establishing of the evaluation method for properties of fresh concrete required in construction.
- c. Establishing of evaluation methods for compressive strength and other properties of hardened concrete.
- d. Establishing of the quality control procedure and evaluation method for concrete strength in structures.

This paper describes the problems of production, transportation and placement when high-strength concrete is applied to reinforced concrete buildings standing in seismic zones and urban areas such as in Tokyo. The results obtained from the preliminary studies and experiments by the High-Strength Concrete Committee will also be briefly introduced.

Keywords: compressive strength; concrete construction; earthquake resistant structures; evaluation; high-rise buildings; high-strength concretes; quality control; reinforced concrete; research; structural design

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INTRODUCTION

The structural design methods and the construction methods of high-rise reinforced concrete buildings 25 to 40 stories high, using high strength concrete with a specified design strength of about 36 to 48 MPa (360 to 480 kgf/cm²) has been well developed and a number of high-rise buildings have been constructed in recent years in Japan. The number of stories of reinforced concrete buildings is closely related to the strength of the concrete being used. Therefore, having high strength concrete becomes essential for multistory buildings. At present, the specified design strength of concrete for reinforced concrete buildings is 36 MPa for 25 stories high, 42 MPa for 30 and 48 MPa for 40 stories high. Higher strength concrete shall be used in the construction of higher multistory buildings. In 1988, the Building Research Institute in the Ministry of Construction started a 5 year research and development project called "Development of High-strength and High-quality Reinforced Concrete Construction System". (Abbreviation: New R C Project), which aims to develop advanced reinforced concrete buildings with high strength and high quality materials.

RESEARCH PLAN FOR THE DEVELOPMENT OF SUPER STRENGTH CONCRETE

The High Strength Concrete Committee under the "New RC" project, which deals with the development of high-strength and super-high-strength concrete, has set up the Material Development Working Group, the Performance Evaluation Working Group, and the Construction Working Group to investigate the following research items.

(1) Material Development Working Group

1. Method of quality examination of cement for high strength and super-high-strength concrete
2. Method of quality examination of the aggregate for high strength and super-high-strength concrete
3. Quality standard and application criteria of the admixture

- for high-strength and super-high-strength concrete
4. Development of the binder for high-strength and super-high-strength concrete (Mixture of cement, silica fume, super minute powder of blast furnace slag and fly ash, etc.)
 5. Design method of mix proportion for high-strength and super-high-strength concrete

(2) Performance Evaluation Working Group

1. Evaluation method of workability of high-strength and super-high-strength concrete
2. Evaluation method of the compressive strength and tensile strength of high-strength and super-high-strength concrete
3. Evaluation of mechanical properties of the confined state in high-strength and super-high-strength concrete
4. Evaluation of the long-term properties of high-strength and super-high-strength concrete
5. Evaluation of the durability of high-strength and super-high-strength concrete
6. Evaluation of the fire resistance of high-strength and super-high-strength concrete

(3) Construction Working Group

1. Development of essential construction techniques for high-strength concrete
2. Evaluation method of quality reliability of high-strength concrete in structures

PRESENT CONDITION OF THE DEVELOPMENT OF HIGH-STRENGTH CONCRETE

The condition of the development of high-strength and super-high-strength concretes for reinforced concrete building mainly designated for the cast-in-place construction use is shown in Table 1. This high-strength and super-high-strength concretes are divided by a design strength limit of 60 MPa. Concrete which has a design strength of less than 60 MPa is likely to be applied to actual buildings in the very near future, while super-high-strength concrete of over 60 MPa has less possibility of actual usage at the moment.

It is possible to manufacture concrete with 60 MPa design strength utilizing materials on the market as seen in Table 1, but it is necessary to take a new look at the standards of quality of cement, admixtures and others. JIS R 5210(*) (portland cement) requires the compressive strength of cement of 28 days of age to be over 300kgf/cm² (about 30 MPa) for a mortar with a water/cement ratio of 65%. The compressive strength of cement on the market is usually around 40 to 45 MPa. It may be possible to manufacture concrete whose design strength is around 36 to 48 MPa design strength using a cement with a compressive strength of 30 MPa and a 30% water/cement ratio. However, it is hardly possible to manufacture specified design strength of 60 MPa

concrete with such a cement.

(*)JIS: Japanese Industrial Standard; the quality standard and test methods for the various industrial products in Japan.

Using available high range water reducing agents and a water/cement ratio of 25 to 30 % makes it possible to manufacture concrete having a 60 MPa specified design strength. JIS A 6204 (chemical admixture for concrete) has established a standard for the quality of the admixtures, but it is dubious whether this standard applies to the admixture for high-strength concrete. Technically speaking, there is no great difficulty in manufacturing 60 MPa design strength concrete using material on the market but it is essential to take a new look at the present standard.

As for a specified design strength of over 60 MPa concrete, the higher the strength, the more difficult it becomes to manufacture. Some experimental manufacturing processes in a large model have successfully made a 100 MPa design strength, mean strength of around 120 MPa concrete[1]. However, if the strength rises up to 120 MPa, the standard deviation of the compressive strength in the large model might exceed 10 MPa, in which case the mean strength tends towards 140 to 150 MPa. Manufacturing such a super-high-strength concrete requires a special manufacturing process and curing method using special materials even in the laboratory. At present, it is rather difficult to manufacture such a concrete on site.

FUNDAMENTAL PROPERTIES OF HIGH-STRENGTH AND SUPER-HIGH-STRENGTH CONCRETE

High-strength concrete, in general, may be fragile and lack toughness so that in utilizing it in buildings, comprehending the mechanical properties and failure characteristics becomes indispensable. The following is the result of examination on the mix proportion and fundamental properties of high-strength concrete performed by the Building Research Institute[2].

(1) Relations between Mix Proportion and Compressive Strength

Several kinds of high-strength concrete specimen(10 X 20cm cylinder) were manufactured with a water/cement ratio 45 to 25%, slump 12 to 21 cm, unit dosage of water 185 to 140 kg/m³, air volume 1 to 4%, using 4 kinds of coarse aggregate (crushed stones; O, T, K, river gravel; R) with an AE water reducing agent, high range water reducing agent, super plasticizer or high range AE water reducing agent of reduced slump-loss type. Fig. 1 shows the result of the compressive strength examination for those concrete specimens cured for 28 days in 20 C water, in comparison with the cement/water ratio and compressive strength. Concrete with crushed stone 'O' is the only non-AE concrete having an air volume 1% and others are AE concrete with an air

volume of 4%.

The relations between cement/water ratio and compressive strength almost forms a straight line as seen in Fig. 1. However, in some samples, when the water/cement ratio becomes 30% to 25%, the increase of compressive strength becomes rather moderate. Also, compared to 1% air volume plain concrete, the 4% air volume AE concrete having the same cement/water ratio shows less compressive strength (15 to 20 MPa less) than that of non-AE concrete.

(2) Tensile Strength

The relation between the compressive strength and the split tensile strength can be seen in Fig. 2. Tensile strength stays within the range of 1/10 to 1/15 of the compressive strength. The ratio of tensile strength to the compressive strength becomes smaller as the compressive strength increases.

(3) Young's Modulus

The relations between the compressive strength and Young's modulus is shown in Fig. 3. The curved line in the figure represents the formula relating compressive strength and Young's Modulus in accordance with the Architecture Institute of Japan. Note the Young's modulus tends to become smaller than the relative formula, when the concrete strength increases. Concrete with gravel R or crushed stones T, in comparison with concrete with crushed stones K, show values of 3×10^3 MPa or 10×10^3 MPa lower at the same compressive strength. The differences of aggregate quality greatly influence the Young's modulus.

(4) Drying Shrinkage

A drying shrinkage process of 200 days is shown in Fig. 4, in different water/cement ratio concrete with crushed stones K, under the condition of water/cement ratio 25 to 40%, unit dosage of water 140 to 185 kg/m³. As seen in this figure, in the case of over 50 MPa high-strength concrete, the drying shrinkage rate does not show much difference in unit dosage of water.

However, the difference of quality in aggregate greatly affects drying shrinkage of concrete. Drying shrinkage of concrete with water/cement ratio 30 to 40% and unit dosage of water 170 kg/m³ was $7.5 - 8 \times 10^{-4}$ with gravel R, was $5.5 - 6 \times 10^{-4}$ with crushed stones and was $8.5 - 9.5 \times 10^{-4}$ with crushed stones T as shown in Fig. 5. It was observed that drying shrinkage became bigger when Young's modulus became smaller.

MECHANICAL PROPERTIES OF CONFINED HIGH-STRENGTH CONCRETE

Confining concrete with spiral sleeve splices increases the capacity of structural members. This method improves compressive

strength and toughness of high-strength concrete. However, the mechanical properties of confined effect or three dimensionally stressed high-strength concrete are still not well understood.

The following are experimental results on the strength and failure toughness of high-strength concrete under the three dimensional stress condition confined by spiral sleeve splices [3].

Four different types of concrete were tested; water/cement ratio 45%, 35%, 25%, water/binder material ratio 25%, the latter having 10% of the quantity displaced by silica fume. Smooth steel 6 mm diameter spiral sleeve splices were used to confine the concrete, of which the yield point was not clear and the maximum tensile load was about 15000 N, as shown in Fig. 6. The concrete was cast into a 15 x 30 cm cylinder mold in which spiral sleeve splices (pitch; 1.5, 3.0, 4.5 cm) was set in order to avoid concrete cover. Unconfined specimen were tested for comparison. Specimens were tested at age of 13 to 15 weeks.

In the compressive strength experiment, displacement quantity between plates was measured by displacement meter (accuracy 1/500mm) as lengthwise strain. Elongation of spiral sleeve splices was measured as well by attaching 2 to 6 wire strength gauges symmetrically to the specimen.

(1) Relations between the pitch of Spiral Sleeve Splices and the Compressive Strength

The relations between the reciprocal number of the pitch of the spiral sleeve splices and the compressive strength of confined specimen were observed as shown in Fig. 7. Compressive strengths increase as the pitch of the spiral sleeve splices narrows. The increase of confined compressive strength is in proportion to the reciprocal number of the pitch of spiral sleeve splices, and no difference by cement/water ratio was observed.

The relations of axial strain obtained from the displacement between plates and axial stress of the confined specimen is shown in Fig. 8. The unconfined specimen was fractured at the maximum stress when the strain reached approximately 0.3. When the pitch of the spiral sleeve splices narrowed, strain against the maximum stress increased. Even when the stress reached its maximum, the confined specimen was not fractured instantly, but retained a certain withstanding force until large deformation.

(2) Influence of Confinement on Compressive Strength

The pitch of the spiral sleeve splices has a significant relation with the confined force of the specimen at maximum stress as shown in Fig. 9. The confined force is obtained from the stress in the spiral sleeve splices being generated by the strain in the spiral sleeve splices. The following formula shows the calculation for confined force.

$$\sigma_y = f_s / r p \text{ ----- (1)}$$

σ_y : confined stress (MPa)

f_s : force generated on the spiral sleeve splices (N)

r : radius of the specimen

p : pitch of between the spiral sleeve splices

This formula shows the confining force increasing when the pitch of the spiral sleeve splices narrows, and the force decreases when the compressive strength decreases.

The relations of confined stress (σ_y) and compressive strength of the confined specimen (σ_c) against the compressive strength of the unconfined specimen (σ_o) can be seen in Fig. 10. The relations of (σ_c/σ_o) against (σ_y/σ_o) is close to a straight line through $\sigma_c/\sigma_o=1$. The gradient of this line is symbolized by k . The compressive strength of the high strength concrete confined specimen is shown by the compressive strength force of an unconfined specimen.

$$\sigma_c = \sigma_o + k \cdot \sigma_y \text{ ----- (2)}$$

The regular value of 'k' is ordinarily around 4 but the value measured in the experiment was between 6 and 8, so rather a high value was shown as seen in Table 2. It is estimated that in high-strength concrete, the angle of failure line increased at the time of fracture.

CONCLUSION

This paper describes the conditions of the development of high-strength concrete for application to high-rise reinforced concrete buildings in Japan, the research plans and the results of a pilot experiment by the high-strength concrete committee in the "New RC" project. Even though high-strength concrete and super-high-strength concrete are being made experimentally in the laboratory, there are still various difficulties in utilizing them in actual buildings from the technical and financial points of view. However, the recent movement toward the development of high-strength and super-high-strength concrete has a keen connection with the revision of concrete making techniques. This movement is also expected to contribute to the improvement of the quality of reinforced concrete constructions.

Reference:

- [1] Toru Kawai, Yoko Yamazaki, Minoru Imai, Daisuke Tachibana, Yasuo Inada, "A Challenge to the Realization of 1000kgf/cm² concrete," Cement Concrete, No. 508, June 1989, pp. 31-38. (in Japanese)
- [2] Fuminori Tomosawa, Yoshihiro Masuda, Michihiko Abe, Hitoshi Tanaka, Masayuki Yasuda, "The Proportion and the Fundamental Properties of High Strength Concrete," 1987 Annual Report of the Building Research Institute, pp. 49-54.
- [3] Yoshihiro Masuda, Masayuki Yasuda, "Mechanical Properties of Confined high-strength concrete," Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, 1989, A, pp. 515-518. (in Japanese)

Table 1. The Development of High-Strength Concrete for
High-rise Reinforced Concrete Building in Japan

Design strength (kgf/cm ²)	Proportioning strength (kgf/cm ²)	Selection of materials				Mix Proportion		Remarks
		Cement	Aggregate	Chemical Admixture	Mineral Admixture	Water binder ratio	Unit dosage of binder(max)	
420-480	600	Possibly manufactured by cement on the market. Present JIS standard is applicable	(*) JASS 5 quality standard is applicable.	Use water reducing agent Present JIS A6 204 quality standard is applicable	JASS 5 quality standard is applicable (*)	35-30 (construction site)	500kg/m ³	Execution of construction works are increasing.
600	800	Possibly manufactured by cement on the market. But, the present JIS standard may not be appropriate.	(*) JASS 5 quality standard is applicable.	Use water reducing agent Need to provide the quality and application standard.	Favourable if super minute powder such as Silica fume, blast furnace slag are mixed. Need to provide the quality and application standard.	30-25 (construction site) 35-30 (laboratory)	600kg/m ³	Experiments have been done with ready-mixed concrete.
1000	1200	Possibly manufactured by cement on the market. But, the present JIS standard is not appropriate.	(*) JASS 5 quality standard is insufficient. Quality standard for aggregate is required.	Use water reducing agent Need to provide the quality and application standard.	The use of super minute powder of Silica fume and Slag is indispensable. Need to provide the quality and application standard.	25-20 (construction site) 25 (laboratory)	700kg/m ³	Possible to produce in the laboratory. Recently a practical manufacturing was reported.
1200	1400 1500	Dubious whether manufactured by using cement on the market or not. Development of new cement might be necessary.	(*) JASS 5 quality standard is inadequate. Might be necessary to consider special aggregate.	Development of super high range water reducing agent is needed.	Development of certain new appropriate mineral is required.	20		Possible to produce in the laboratory by the use of special material and method of producing and curing.

(*) JASS 5; Japanese Architectural Standard Specification, Chapter 5 Reinforced Concrete Work.

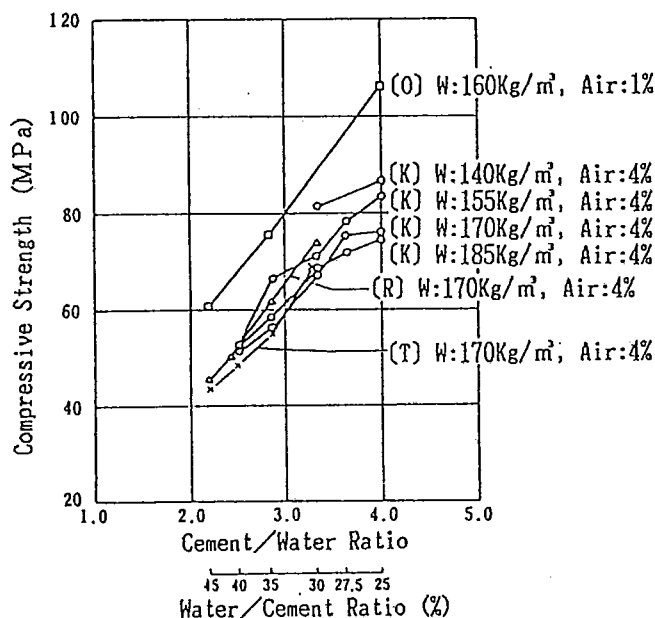


Fig. 1. Relations between Cement/Water Ratio and Compressive Strength

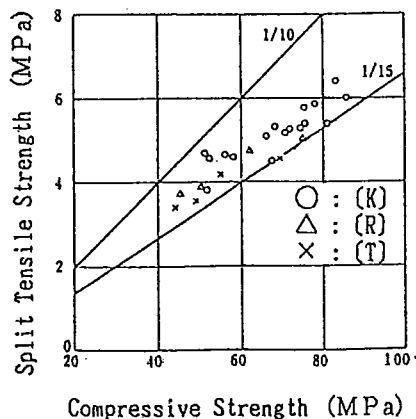


Fig. 2. Relations between Compressive Strength and Split Tensile Strength

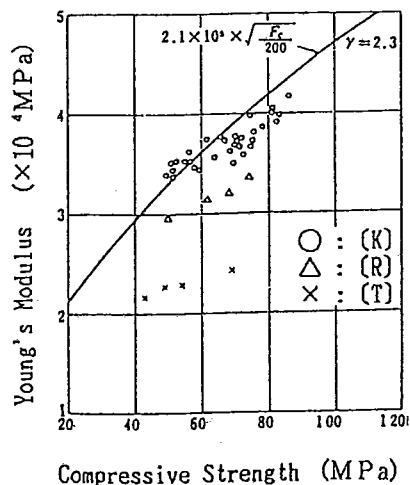


Fig. 3. Relations between compressive Strength and Young's Modulus