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※ 含密集鋼筋 RC 構造採用 SCC 提昇耐震功能之機理探討※

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Effect of Consolidation on Bond of Reinforcement in Concrete of Different Workabilities

Yin-Wen Chan, Yong-Guo Chen, and Yi-Shi Liu
Department of Civil Engineering
National Taiwan University
Taipei, 106
TAIWAN

The effect of consolidation on concrete-steel bond strength was investigated. Key variables included the degree of consolidation and concrete workability. D32 (No.10) deformed reinforcing bars were used with a 250 mm embedment length. Three different types of concrete were adopted, including normal concrete with low slump (75 mm), high-performance concrete with high slump (220 mm), and self-compacting concrete. Rebar pullout tests were conducted to measured the bond strength of rebars in concrete subjected to various consolidation conditions. Different consolidation conditions were adopted to simulate various situations that might possibly occur during practical concrete placement, including standard vibration, over-vibration, no vibration, and improper vibration.

The experimental results indicate that consolidation is absolutely important to the bond strength development of rebars in normal concrete. The bond strength of normal concrete is significantly reduced when no vibration is applied. The application of vibration in HPC is so crucial that over-vibration or improper vibration would result in substantial reduction in bond strength. Without any consolidation, Self-compacting Concrete is capable of developing remarkably higher bond strength than the control case. Furthermore, the application of vibration in SCC may affect the bond strength and should be prevented.

ACI member **Yin-Wen Chan** *is an associate professor of Civil Engineering at the National Taiwan University, Taipei, Taiwan. He is a member of TG 8.4, Self-compacting Concrete, of fib Commission 8, Concrete. He also serves as the chairman of High-performance Concrete Committee of the Chinese Society of Structural Engineering (Taiwan). His research interests include high-performance concrete, fiber reinforced cement-based materials, and bond properties of reinforced concrete.*

Yong-Guo Chen *received his MS in 2001 from National Taiwan University, Taipei, Taiwan.*

Yi-Shi Liu *is currently a teaching assistant in the Department of Civil Engineering at National Taiwan University. He received his MS in 2002 from the same department.*

INTRODUCTION

In the construction of reinforced concrete structures, consolidation has to be applied to the concrete mixture to ensure the quality of concrete placement. Insufficient consolidation may result in defects, such as honeycombs, voids, or vacancies, in reinforced concrete members. These construction deficiencies would lead to reductions in durability and structural performance. However, in members with congested reinforcement or with large dimensions, consolidation may not always be an easy task. The selection of concrete with proper workability is usually governed to resolve the difficulties in concrete placement. With the increasing use of congested reinforcement in moment-resisting members, e.g. due to seismic consideration, there is a growing interest in specifying high workability concrete, such as high performance concrete (HPC).

In general, HPC possesses high strength as well as high workability and is used as a solution to the situation that demands particularly high durability. In order to resolve the problems with concrete placement, a special type of concrete, called self-compacting concrete (SCC), has been developed that requires no consolidation at all. It has been verified that with non-vibration construction, the application of self-compacting concrete can enhance the uniformity of materials in RC members and, thus can help to ensure the designed structural performance[1,2]. However, the practice of non-vibration concreting is totally against the conventional practice of construction that demands sufficient consolidation during concrete placement. Apparently, the application of SCC requires a certain extent of training and adjustment in the construction practices of workers. For this purpose, it is desired to know how the task of consolidation should be adjusted in the placement of SCC, or what the effect would be if vibration is still applied during the placement of SCC.

In building construction, internal motor-driven vibrators are widely used in concrete placement. Consolidation by vibration consists of two stages. The first stage is subsidence or slumping of concrete and the second is the removal of entrapped air bubbles. In general, the two stages may occur simultaneously, while the second stage takes longer duration. At the completion of the first stage, honeycombing can be eliminated and large voids between coarse aggregates will be filled with mortar. For concrete with high slump, the need of vibration to reduce honeycomb is less. However, the need of vibration to remove the entrapped air remains the same. Therefore, the extent of vibration may be reduced but not be omitted. Thus, for high slump concrete, such as HPC, what would be the appropriate practice for applying internal vibration is a frequently asked question at the job sites. Engineers would also like to know the possible influence if the same degree of vibration, as in the case of ordinary concrete, is applied to the case of HPC.

Several factors affecting the bond strength have been studied by a number of researchers. These factors include the composition materials, compressive strength of concrete3-6, and testing methods and apparatus7-9. Research in the influence of workability of concrete on bond properties is very limited10.

In this paper, the effect of internal vibration by electrical motor-driven vibrator on the bond strength of rebars in concretes of different workability was investigated. Different consolidation conditions were adopted to simulate various situations that might possibly occur during practical concrete placement, including standard vibration, over-vibration, no vibration, and improper vibration. During the casting of specimens, the concrete mixes were subjected to various conditions of internal vibration, including no vibration, vibration in different durations, and vibration directly in contact with the rebars. The experimental program varied the vibration duration to quantify the degree of vibration. Additionally, two more conditions that are likely to occur in practice were checked, including no vibration for simulating the case of insufficient consolidation and vibration against rebar for simulating the case of improper practice in applying vibration.

Keywords: Consolidation; bond strength; high-performance concrete; self-compacting concrete; vibration; motor-driven vibrator.

RESEARCH SIGNIFICANCE

This research has special significance in construction practice and materials specification for reinforced concrete projects. The experimental program varies the vibration duration to quantify the degree of vibration. Additionally, two more conditions that are likely to occur in practical situation are adopted, including no vibration for simulating the case of insufficient consolidation and vibration against rebar for simulating the case of improper practice in applying vibration. The experimental results clearly indicate that the degree of vibration as well as the workability of concrete may tremendously affect the bond strength between rebars and concrete. For special concrete such as HPC and SCC, necessary adjustments in consolidation practice are particularly important and essential.

EXPERIMENTAL PROGRAM

Single rebar pullout tests were conducted to measure the bond strength of horizontal deformed reinforcing steel bars in various concretes of different vibration conditions.

Materials

Three types of concrete of different levels of workability were used in the experimental program, including normal concrete (NC, with a slump less than 75 mm) as the comparatively low slump concrete, high performance concrete (HPC, with a slump of over 200 mm) as the high slump concrete, and self-compacting concrete (SCC) as an extremely high workability concrete.

The mix proportions of the three different concretes are given in Table 1. A typical mix proportion of normal concrete is selected with moderate w/c ratio and workability. The mix proportion of HPC is similar to that of NC except slag and superplasticizer are incorporated. In the case of NC, only a minimal amount of water reducer is used, whereas, in HPC, 60 kg/m^3 of slag and superplasticizer with a dosage of 3.46 kg/m^3 are used to enhance the workability of the mixture. For SCC, a high content of pozzolanic materials, 200 kg/m^3 of slag and fly ash in total, as well as a particular type of superplasticizer are adopted to achieve the self-compactability.

The fresh concrete properties of the three different concretes are summarized in Table 2. According to Table 2, the slumps of NC and HPC as measured before casting are 75 and 220 mm, respectively. In addition to the slump, there are several other essential test items for fresh concrete properties of SCC as recommended by JSCE[11], including the slump flow, V-funnel test, and U-box test. A slump flow of 540 mm is measured for SCC, indicating a good deformability. The discharge time from the V-funnel provides an index of viscosity of SCC. Finally, the U-box test verifies the “self-compactability” of the concrete mixtures. According to the recommendations by JSCE, a concrete with a filling capability of the U-box tests exceeding 300 mm is qualified as SCC. All of the test items have to be verified before the casting of the specimens.

The information of the deformed reinforcing steel bars is given in Table 3. D32 rebars (No. 10) with yield strength of 600 MPa are used in the experimental program.

Preparation of Specimens

The pullout specimens are prepared with the horizontal rebars protruding from the vertical surface on the side of the specimens. The dimensions of the pullout specimen, the layout of the horizontal rebars, and the assembled formwork are shown in Figure 1 and 2. As shown in Figure 1, there are three horizontal rebars installed 300 mm apart in each specimen. Some lateral reinforcements are also arranged to assure the integrity of the specimen. Furthermore, bond breakers are installed on both ends of the embedded portion of the horizontal rebars to prevent stress concentration and premature splitting type of pullout failure. Therefore, by subtracting the length of bond breakers, the net embedment length of rebars is 250 mm.

In the casting of specimens, concrete was first discharged into the formwork with the rebars assembled. The concrete in the formwork was then subjected to various conditions of consolidation (described below). For the casting of SCC specimens, concrete was discharged gradually on one side of the formwork and allowed to flow to the other side. The discharge of SCC was controlled in a way that the elevation of horizontal surface of SCC could rise steadily, submerge the rebars, and, eventually, fill to the top of the formwork.

After casting, the specimens were sealed and stored in a temperature-controlled environment. All specimens were demolded after 3 days and kept moist until the age of 28 days for pullout test.

Application of Vibration

ACI 309R recommends that the vibrator should be manipulated in an up and down motion, generally in an interval for 5~15 seconds[12,13] for each point of application. The displacement between insertions should be about 1 1/2 times the radius of action, and should be such that the area visibly affected by the vibrator overlaps the adjacent just-vibrated area.

An electric motor-driven vibrator with a head diameter of 50 mm (2 in.) is used to consolidate the concrete during casting of the specimens. According to ACI 309R, the radius of action of this type of vibrator ranges between 180 and 360 mm[1]. Therefore, in this case, vibration applied in a distance of 300 mm between insertions for 10 seconds is regarded as the standard vibration practice and the control case. As shown in Figure 3(a), the standard vibration practice is applied in a way that the vibrator is inserted vertically into concrete at a distance approximately 150 mm from the rebars. The depth of the vibration insertion is 150 mm so that the center of the vibrator head is at the same elevation of the rebars.

It is noted that the vibrator is only inserted into the points specified in Figure 3(a). Different degrees of consolidation are provided by various vibration durations, including 10 (control case), 20, and 30 seconds. The vibrator is withdrawn immediately after the specified acting duration. The application of vibrator is controlled in such a way to avoid all other possible factors that may affect the conditions of consolidation.

In addition, a situation without any vibration during casting of specimens is also adopted for reference. In consideration of the situation that the vibrator may unavoidably be in contact with the reinforcement during the placement of concrete, an additional case with the vibration applied against the rebars is also included in the experimental program. As shown in Figure 3(b), the vibrator is applied directly in contact with the rebars for 10 seconds.

The specimens and the corresponding conditions of vibration of the experimental program are summarized in Table 4.

The case without any vibration may correspond to the situation of insufficient or poor consolidation. For other cases, vibration is applied in different duration, including 10, 20, and 30 seconds. If the case of vibration for 10 seconds serves as a standard consolidation practice, the cases of vibration for 20 and 30 seconds represent the situation of over-consolidation.

In addition, when consolidation is applied, it is unavoidable that the vibrator may directly contact the reinforcement. When this occurs, the bonding between reinforcement and concrete will be affected. Therefore, the case that the vibrator is applied directly in contact with the rebar can be regarded as a case of improper consolidation.

Pullout Test Setup

The pullout test setup is shown in Figure 4. Single rebar pullout tests were conducted. The protruding rebar is connected to an extension rod by a coupler. A loadcell, a hydraulic jack, a mounting system, and an LVDT fixture are facilitated as shown in Figure 4. The hydraulic jacking system is adopted to apply a concentric pullout force to the rebar. When bond slip occurs, the displacement of the rebar can be obtained from the measurement of the LVDT attaching to the rebar. During testing, pullout load and rebar slip displacement are measured and recorded automatically. More detailed information on the pullout test setup is available elsewhere[14,15].

RESULTS AND DISCUSSION

Observation on Specimens

After demolded, the appearance of the specimens subjected to various conditions of consolidation is examined. As shown in Figure 5, for the case of normal concrete without vibration (NC-00), a poor casting result can be observed that honeycombs and voids are all over the entire specimen. When consolidation is not applied, it is not unexpected to obtain such a casting result for concrete with a slump of only 75 mm. The casting deficiencies observed in the case of NC-00 can be eliminated if a certain amount of vibration is applied. With various extents of consolidation, the casting deficiency is no longer found for all other cases of normal concrete except NC-C-00. For the case of NC-C-10, the vibration is applied upon the rebar directly. As a result, it can be seen from Figure 6 that, in comparison with NC-00 (Figure 5), the filling of concrete adjacent to the rebar has been improved. However, there are still significant casting deficiencies away from the rebars, especially in the bottom part of the specimen where the vibrator does not reach.

For HPC, the casting results are mostly satisfactory based on visible appearance of the specimens except the case of HPC-00 (no consolidation). As can be seen in Figure 7, HPC does not fill into corners of the formwork properly when consolidation is not applied. Apart from the corners, the casting of HPC appears to be acceptable for the rest portion of Specimen HPC-00. This observation indicates that, even for concrete with a high slump such as 220 mm in this study, at least a minimal amount of consolidation is required to appropriately place the concrete. Without consolidation, there can be space between reinforcing bars or corners in the formwork that concrete may not fill in properly.

For all cases of SCC that has been verified of its self-compactability, with or without consolidation, the casting results are acceptable based on the visible appearances, e.g. Figure 8.

Interpretation of Bond Strength

In the pullout tests, the pullout load and rebar slip distance are recorded. All the tested pullout specimens failed in direct pullout of rebars. No splitting or cracking was observed on the surface of tested specimens. The pullout load-versus-slip distance relations are then used to interpret the bond strength of rebars in various types of concrete.

Typical pullout load-versus-displacement curves are given in Figure 9. The average bond stress can be obtained from the pullout loads divided by the contact area of the embedded rebar to concrete. The contact area of embedded portion of rebars is given by the multiplication of embedment length and perimeter of the rebar.

The critical bond strength concept is adopted to interpret the bond strength for each case. The critical bond strength is the bond stress corresponding to a slip distance of 0.25 mm[14,16]. In comparison with the ultimate bond strength, i.e. the maximum bond stress, the critical bond strength possesses a better correlation to the required development length as recommended by ACI Code provisions[17]. In general, the use of the ultimate bond strength tends to over-estimate the bond between reinforcements and concrete. Henceforward, the pullout load and bond stress corresponding to a slip distance of 0.25 mm will be adopted for the following discussions.

The obtained pullout loads of all specimens are summarized in Table 5 and the calculated bond strength are given in Table 6. In general, except three cases, there are three individual measurements of pullout load for each case. The bond strength for each case will be obtained from the average of the three individual pullout results. In the cases of NC-C-10, HPC-S-10, and SCC-S-20, one of the three rebars fails to be pulled out due to the cracking formed around it as a result of the pullout process of other rebars.

According to the provisions of ACI 318-95[17], the bond strength can be greatly influenced by the compressive strength of concrete. In order to compare the bond properties of different types of concrete, the influence of concrete compressive strength needs to be taken into account. It can be done by normalizing the measured bond strength by a factor related to $\sqrt{f_c'}$. Since the nominal compressive strength of the concretes used in this study is designated as 28 MPa, the measured bond strength can thus be normalized by multiplying a factor of $\sqrt{\frac{28}{f_c'}}$. The normalized bond strengths are summarized in Table 7.

Effect of Vibration Time

The effect of vibration time on bond strength can be examined based on the results summarized in Figure 10. For each case, there are three individual bond strengths and the results are all plotted in Figure 10. In order to observe the effect of vibration time, the averages of the three individual bond strengths for each case are connected by segments. As the vibration duration increases from 10 to 30 seconds, the influence on bond strength varies with different types of concrete. There is a slightly increase in bond strength for normal concrete. The bond strength of HPC decreases significantly with the increase of vibration time from 10 to 20 seconds. For SCC, the influence of vibration time is not remarkable. Apparently, the effect of vibration time on bond strength varies with the concrete type and, thus, needs to be examined for each type of concrete.

The cases of no vibration are also involved in Figure 10, it can be seen that, without any vibration, the average bond strength of SCC is significantly higher than those of the other two types of concrete. Without consolidation, the average bond of normal concrete is only approximately 50% of that of SCC. In fact, the average bond strength of SCC without consolidation is the highest one among all cases in this experimental program. This observation indicates that, without the need of any consolidation, SCC is capable of filling into the formwork and around the reinforcements and, consequently, develops superior bond properties.

The individual bond strengths of NC-S-10, HPC-S-10, and SCC-00, are given in Figure 11. The bond ratios, the average bond strength of each case divided by that of NC-S-10, are also provided. These three cases are particularly compared because NC-S-10 and HPC-S-10 may represent the theoretical bond strength under the standard consolidation practice and SCC-00 gives the bond strength under the non-consolidating condition, which is supposed to be applied in placing SCC.

If the bond strengths of normal concrete and HPC under standard vibration practice are regarded as the desirable bond strength, SCC is apparently capable of developing much higher bond strength under a non-vibration concrete placement practice as shown in Figure 11. According to the bond ratios given in Figure 11, the bond strength of SCC-00 is approximately 20% higher than those of NC-S-10 and HPC-S-10 on the basis of same compressive strength. Comparing to normal concrete or HPC, the superior bond properties of SCC can be attributed to a much more uniform and consistent material structure[14] in concrete when vibration is not applied in SCC.

Normal Concrete (NC)

As shown in Figure 12, comparing to the case of standard vibration (10 seconds), the bond strength of normal concrete is significantly deteriorated if no consolidation is applied (0 second). The average bond strength of NC-00 is only 60% of that subjected to standard vibration (NC-S-10). In addition, the three individual test results of NC-00 show a wide range of variation. This is consistent to the observation in Figure 5 that, without any consolidation, the filling capability of low-slump normal concrete is poor and the reinforcements in the formwork may not be properly surrounded and bonded. Therefore, the bond measurements of NC-00 fluctuate between 32 and 44 with a C.O.V. of 17.5%. This indicates that consolidation is extremely important for normal concrete with low or medium slump.

If the vibration time is increased from 10 to 30 seconds, slightly increase in bond strength can be observed. The increase in the average of bond strength of NC-S-30, as compared to NC-S-10, is approximately 13%. However, this increase in bond strength should not be taken as an advantage because the increase in vibration time enhances the variation in individual bond measurement of NC-S-30 (with a C.O.V. of 5.5%).

The test result of normal concrete confirms that consolidation is important for the bond between reinforcements and concrete. Furthermore, the results also indicate that over-consolidation may not affect the bond in the case of low slump concrete.

High Performance Concrete (HPC)

According to Figure 13, the comparison between HPC-00 and HPC-S-10 indicates that, if consolidation is not applied, the effect on bond strength is minimal. However, when the vibration time increases, the bond strength decreases significantly. The average bond strengths of HPC-S-20 and HPC-S-30 are only approximately 80% of that of HPC-S-10. The decrease in bond strength can be due to bleeding or segregation in concrete when the excessive vibration is provided. This can also be supported by the remarkable variation in the three individual test results of HPC-S-30. As shown in Figure 13, significant variation in the bond strength measurements of HPC-S-30 can be observed. According to Table 7, the C.O.V. of HPC-S-30 is 11.6%.

The results of HPC suggest that the application of vibration in high slump concrete is crucial. When over-consolidated, the bond strength may undergo drastic reduction.

Self-Compacting Concrete (SCC)

The measured bond strengths of SCC under various vibration times are summarized in Figure

14. As mentioned previously, the bond strength of SCC-00 is the highest one of all. Once vibration is applied to SCC, bond strength decreases. As compared to SCC-00, the reduction in bond is approximately 15% in average for SCC-S-10, SCC-S-20, and SCC-S-30. Furthermore, the application of vibration to SCC not only results in reduction in bond strength, but also increases the C.O.V. in bond measurements according to Table 7. The C.O.V. of the three individual bond measurements of SCC-00 is within 4%, whereas those of SCC-S-1-, SCC-S-20, and SCC-S-30 range between 7.7% and 11.5%.

According the principle of SCC[1,2], the mix proportion of SCC has to be optimized to obtain the desired rheological properties, including the capability of flowing under gravity and the sufficient cohesiveness to avoid segregation while filling into the formwork and reinforcements. The application of vibration, which may reduce the cohesiveness, can destruct the optimized rheology and microstructure of SCC due to bleeding or segregation. Consequently, the bond strength would also be affected and reduced. Therefore, for SCC, consolidation in concrete placement should be strictly prevented.

Vibration against Rebars

In concrete placement, motor-driven vibrators are the most popular way to provide consolidation. Although it has been mentioned in the guide or recommendation for concrete placement that one should not contact reinforcements with the vibrator, it is sometimes unavoidable that the vibrator may be in contact with reinforcements practically. When this occurs, the bond between reinforcements and concrete may be affected.

The obtained bond strengths of the cases with vibrator applied in contact with the rebars are summarized in Figure 15 along with the cases of standard vibration and non-vibration. It can be seen from Figure 15 that the bond strength of HPC and SCC will be significantly affected if the vibration is applied directly onto the rebars. Especially for HPC, the reduction in bond strength may exceed 30% (bond strength of HPC-C-10 being only 68% of that of HPC-S-10). As shown in Figure 13, excessive vibration is absolutely harmful to the bond strength of HPC. Vibration applied directly upon rebars is an even worse case than over-consolidation, although the time of vibration against the rebar is only 10 seconds. For SCC, the bond strength with vibration applied upon rebars is also lower than the cases of various vibration times. However, the reduction is less significant as compared to HPC.

For the case of low slump concrete, the bond strength does not seem to be affected with vibration against rebars. This is consistent with the finding that the bond strength of normal concrete does not decrease with the increase in vibration time (Figure 12). According to the appearance of demolded specimen shown in Figure 6, vibration against the rebar does help to consolidate the local area surrounding the rebar. Nevertheless, Figure 6 also shows clearly that the surface of the specimen is full of defects except the area around the rebars. When the vibration is applied against the rebars, only the region around the rebars is consolidated. Most of the concrete in the specimen remains unconsolidated. Therefore, vibration against the rebar is not a valid consolidation practice and should be strictly avoided.

Although the comparison in the average bond strength suggests that the condition of consolidation does not seem to influence the bond strength of normal concrete, the variation in individual bond measurement (the C.O.V. of Table 7), however, reveals that the uncertainties in the bond of normal concrete is actually enhanced when over- or improperly consolidated. Therefore, in the placement of low slump concrete, the standard consolidation practice, e.g. that recommended by ACI 309R, should still be followed.

In summary, the experimental results indicate that consolidation is absolutely important to the bond strength development of rebars in normal concrete. The bond strength of normal concrete will be significantly reduced if no vibration is applied. The application of vibration in HPC is very crucial, over-vibration or improper vibration will result in substantial reduction in bond strength. Without any consolidation, SCC is capable of developing remarkably higher bond strength than the control case. Furthermore, the application of vibration in SCC may affect the bond strength and should be prevented.

CONCLUSIONS

1. For normal concrete with low slump, the application of consolidation during concrete placement is important. Insufficient or no consolidation may result in a significant reduction in bond strength and even structural performance. The bond strength of normal concrete does not seem to be affected by over-consolidation or improper consolidation. In other words, the skill or practice of consolidation is essential but not crucial for the case of low slump normal concrete. The cohesiveness of the low slump normal concrete helps to prevent segregation or bleeding. Therefore, the bond strength will not be affected remarkably by various vibration conditions as long as it has been consolidated.
2. The application of consolidation is crucial for high performance concrete. Excessive or improper consolidation can result in substantial reduction in bond strength of HPC. The reduction in bond strength can be as much as 30%. In contrast, the bond of HPC is not affected too much if consolidation is insufficient. However, if no consolidation is applied, the filling of concrete will not be satisfactory. Honeycombs and voids can be observed near the corners of the specimens.
3. For self-compacting concrete, the application of consolidation should be avoided. When vibration is applied, the bond strength may decrease for 10% or more. Vibration applied directly on rebars will be more harmful to the bond of SCC than the cases of over-consolidation.
4. Comparing the bond strength of normal concrete or HPC under standard vibration practice with that of SCC without any vibration, the bond strength of SCC is significantly higher than that of normal concrete or HPC given the same compressive strength. In the case of congested reinforcements, the advantages of SCC on construction adequacy and on structural performance are thus verified.

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Table 1 Mix proportions

(in kg/m^3)

Material	NC	HPC	SCC
Cement	345	300	220
Slag	-	60	80
Fly ash	-	-	120
Water	192	192	182
Sand	863	835	1030
Gravel	938	945	724
Superplasticizer/ Water reducer*	1.31	3.46	5.04
Water-to-cementitious materials ratio	0.556	0.533	0.433
Sand ratio (S/A)	0.47	0.48	0.59

* For SCC, Polycarboxylic acid-based superplasticizer is used; ordinary water reducer is used in normal concrete mixture

Table 2 Fresh concrete properties of various materials

Test	SCC	NC	HPC
Slump (mm)	265	75	220
Slump flow (mm)	540	-	-
V-funnel test (sec)	2.97	-	-
U-box test (mm)	320 (300*)	-	-
Air content (%)	5	1.5	1.1
Unit weight (kg/m^3)	2354	2338	2332

* According to JSCE[11], concrete with a "U-box" filling capability of 300 mm is qualified as SCC.

Table 3 Information of the reinforcing steel bars used

Rebar	Yield strength (MPa)	Tensile strength (MPa)	Diameter (mm)	Area (mm^2)	Perimeter (mm)
D32 (No.10)	600	640	32	814.3	101

Table 4 Specimen labeling and variables of pullout test

Material		SCC[#]	NC[*]	HPC[&]
Standard vibration (S)	0 sec.	SCC-00	NC-00	HPC-00
	10 sec.	SCC-S-10	NC-S-10	HPC-S-10
	20 sec.	SCC-S-20	NC-S-20	HPC-S-20
	30 sec.	SCC-S-30	NC-S-30	HPC-S-30
Vibration against rebar for 10 sec. (C)		SCC-C-10	NC-C-10	HPC-C-10

[#] Self-compacting concrete (with self-compactability)
[*] Normal concrete (with a comparatively low slump of 75 mm)
[&] High-performance concrete (with a high slump of 220 mm)

Table 5 Pullout loads for all specimens at the slip distance of 0.25 mm

Specimen	Pullout load (kN)			
	#1	#2	#3	Average
NC-00	91.8	87.3	119.4	99.5
NC-S-10	166.9	157.6	169.7	164.7
NC-S-20	177.1	172.9	177.1	175.7
NC-S-30	199.4	180.0	183.6	187.7
NC-C-10	178.0	158.0	-	168.0
HPC-00	165.9	150.4	154	156.8
HPC-S-10	151.9	-	171.1	161.5
HPC-S-20	133.9	126	123.5	127.8
HPC-S-30	149.8	118.7	137.1	135.2
HPC-C-10	103.5	113.9	112.7	110.03
SCC-00	205	190	201	199
SCC-S-10	190	162	165	172
SCC-S-20	175	-	157	166
SCC-S-30	151	170	190	170
SCC-C-10	175	138	167	160

[*] The pullout loads corresponding to a bond slip of 0.25 mm are drawn from the pullout load-versus-slip relation

Table 6 Interpreted bond strength

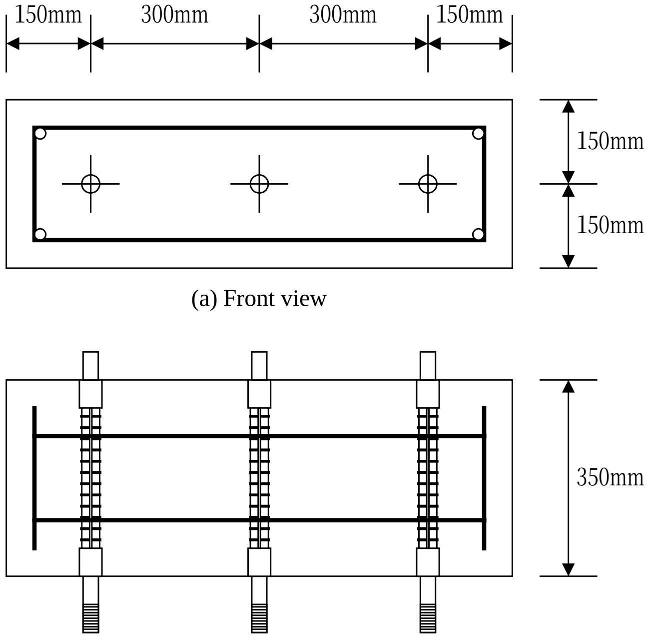
Specimen	Bond strength* (MPa)			
	#1	#2	#3	Average
NC-00	3.63	3.46	4.73	3.94
NC-S-10	6.61	6.24	6.72	6.52
NC-S-20	7.01	6.84	7.01	6.96
NC-S-30	7.89	7.13	7.27	7.43
NC-C-10	7.05	6.26	-	6.65
HPC-00	6.57	5.95	6.10	6.21
HPC-S-10	6.01	-	6.77	6.39
HPC-S-20	5.30	4.99	4.89	5.06
HPC-S-30	5.93	4.70	5.43	5.35
HPC-C-10	4.10	4.51	4.46	4.36
SCC-00	8.12	7.52	7.96	7.86
SCC-S-10	7.52	6.41	6.53	6.82
SCC-S-20	6.93	-	6.22	6.57
SCC-S-30	5.98	6.73	7.52	6.74
SCC-C-10	8.12	7.52	7.96	7.86

* The bond strengths are calculated from the pullout loads in Table 11 divided by concrete contact area (embedment length = 250 mm; bar diameter = 32 mm)

Table 7 Normalized bond strength

Specimen	Modified bond strength* (MPa)				C.O.V. (%)
	#1	#2	#3	Average	
NC-00	3.33	3.17	4.34	3.61	17.47
NC-S-10	6.06	5.73	6.17	5.98	3.85
NC-S-20	6.43	6.28	6.43	6.38	1.38
NC-S-30	7.24	6.54	6.67	6.82	5.50
NC-C-10	6.47	5.74	-	6.10	8.41
HPC-00	6.36	5.76	5.90	6.01	5.17
HPC-S-10	5.82	-	6.56	6.19	8.41
HPC-S-20	5.13	4.83	4.73	4.90	4.24
HPC-S-30	5.74	4.55	5.25	5.18	11.57
HPC-C-10	3.97	4.36	4.32	4.22	5.16
SCC-00	7.61	7.06	7.46	7.38	3.91
SCC-S-10	7.06	6.02	6.13	6.40	8.92
SCC-S-20	6.50	-	5.83	6.16	7.67
SCC-S-30	5.61	6.31	7.06	6.33	11.45
SCC-C-10	6.50	5.12	6.20	5.94	12.17

* Bond strengths in Table 12 are modified by a factor of $(28/f_c')^{1/2}$ to take into account of the influence of compressive strength of different concrete materials



(a) Front view

(b) Top view

Figure 1 Dimensions of pullout specimen and the layout of rebars

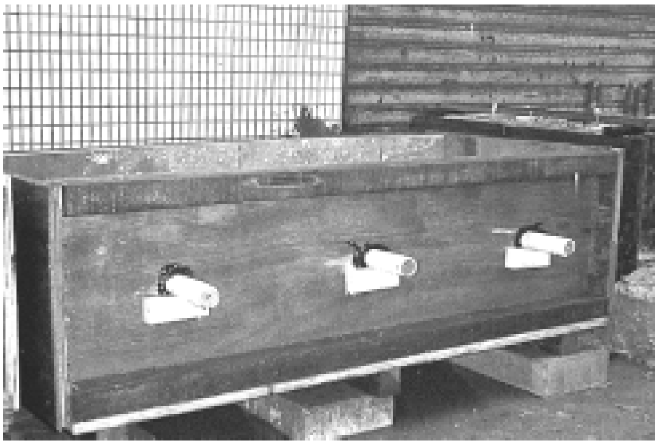


Figure 2 Formwork of pullout specimen

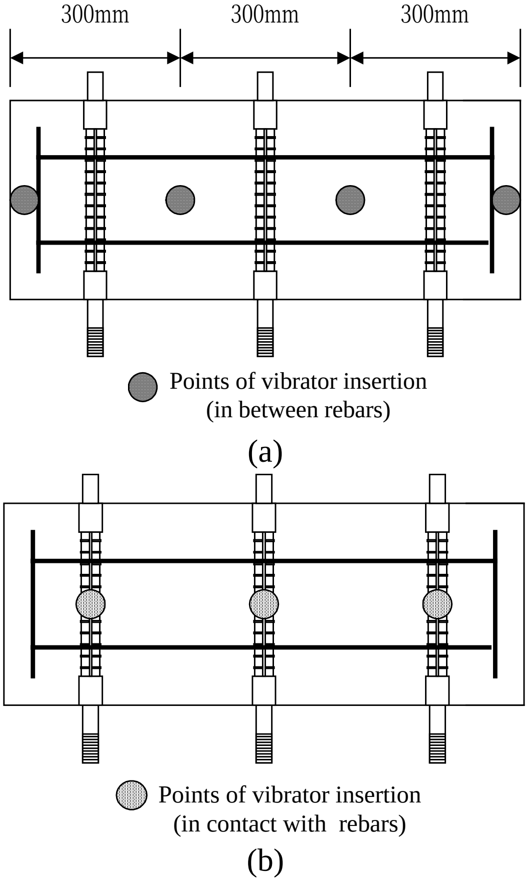


Figure 3 Points of vibration: (a) standard vibration practice; (b) vibration against the rebars

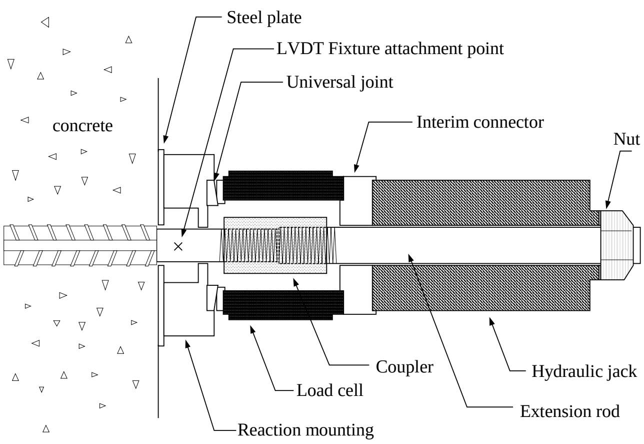


Figure 4 Pullout test setup

Figure 5 Appearance of Specimen NC- 00 (normal concrete, no vibration)

Figure 6 Appearance of NC-C-10 (normal concrete, vibration against rebar for 10 seconds)


Figure 7 Appearance of HPC-00 (HPC, no vibration)


Figure 8 Appearance of SCC-00 (SCC, no vibration)

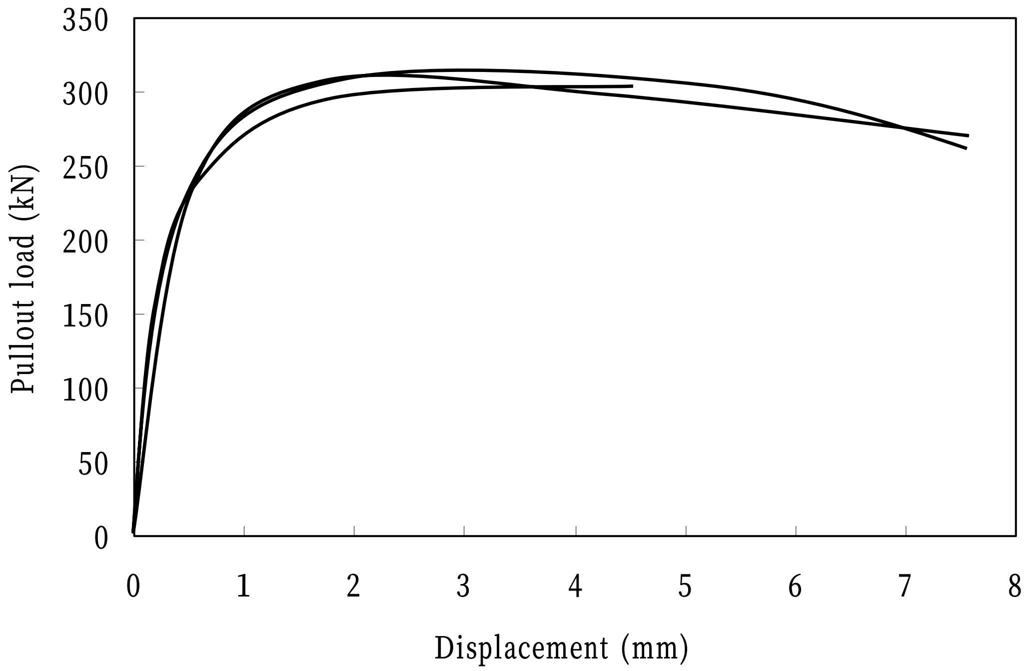


Figure 9 Typical pullout curves (SCC-00)

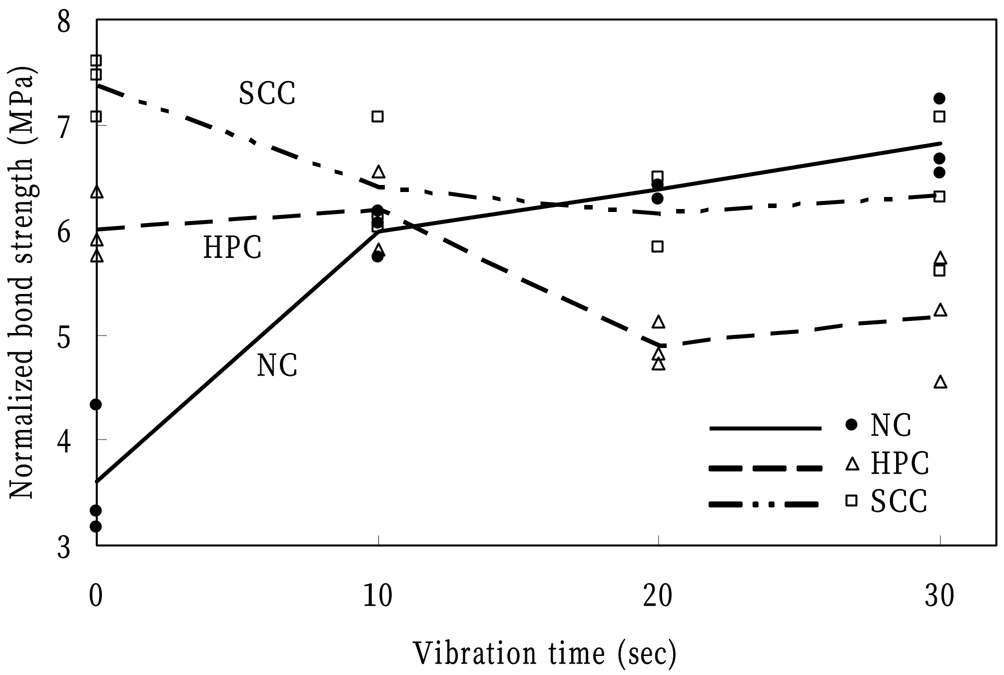


Figure 10 Effect of vibration time on bond strength of various concretes

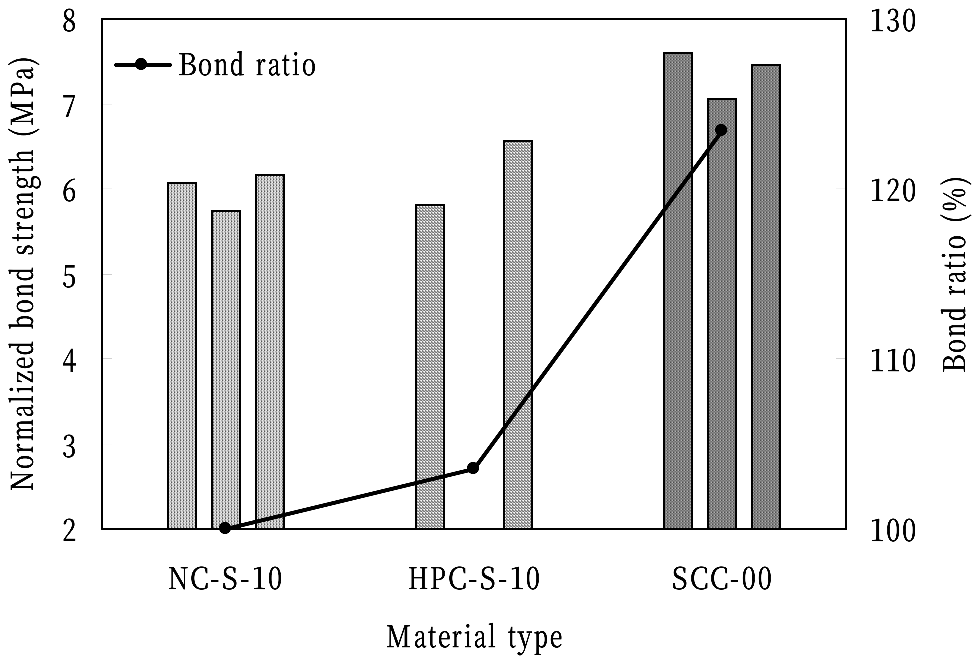


Figure 11 Comparison of bond strength of normal concrete and HPC under standard consolidation and SCC by non-vibration placement

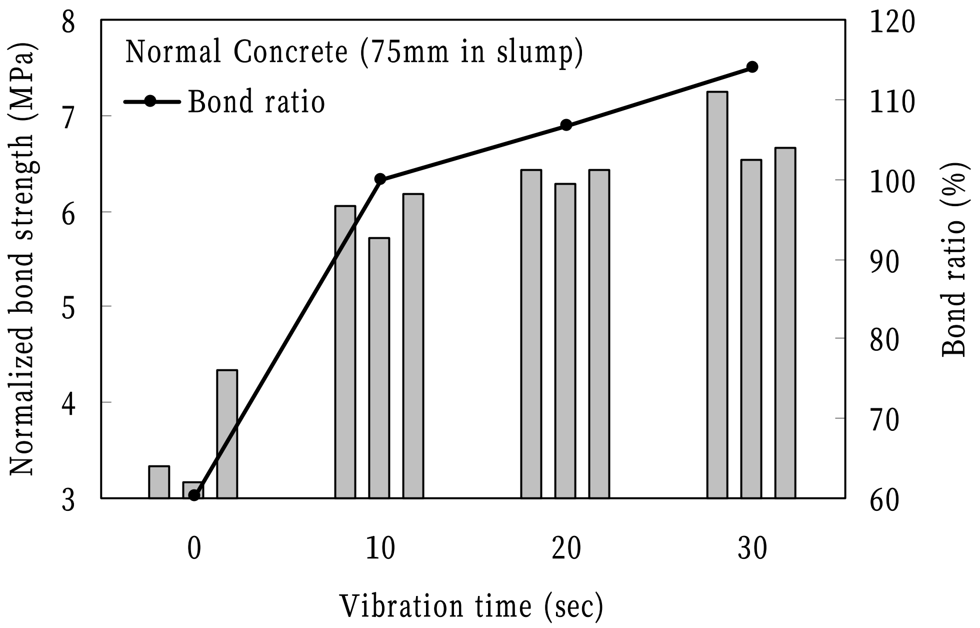


Figure 12 Bond strengths of normal concrete in various consolidation conditions

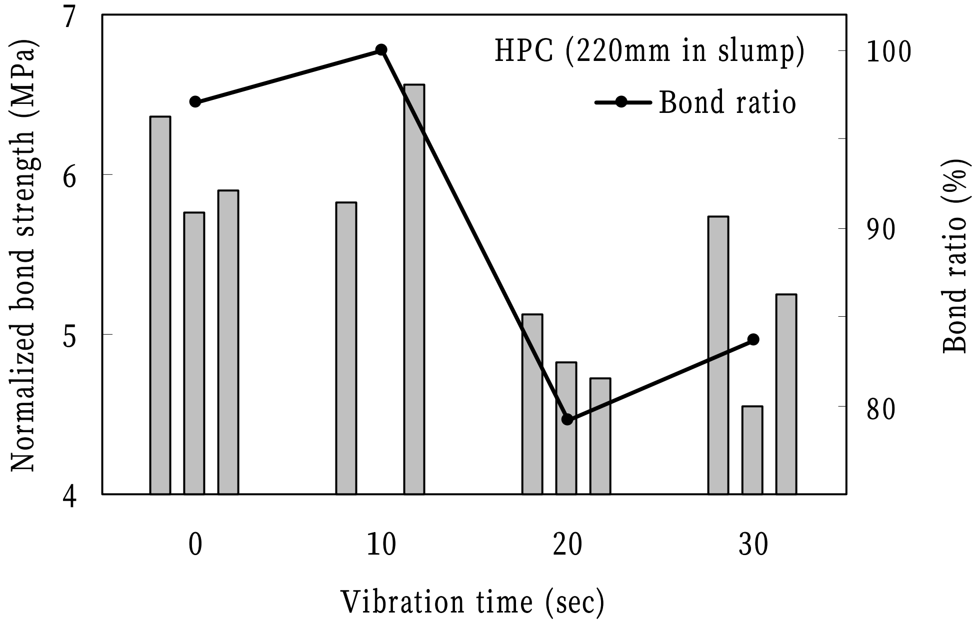


Figure 13 Bond strengths of HPC in various consolidation conditions

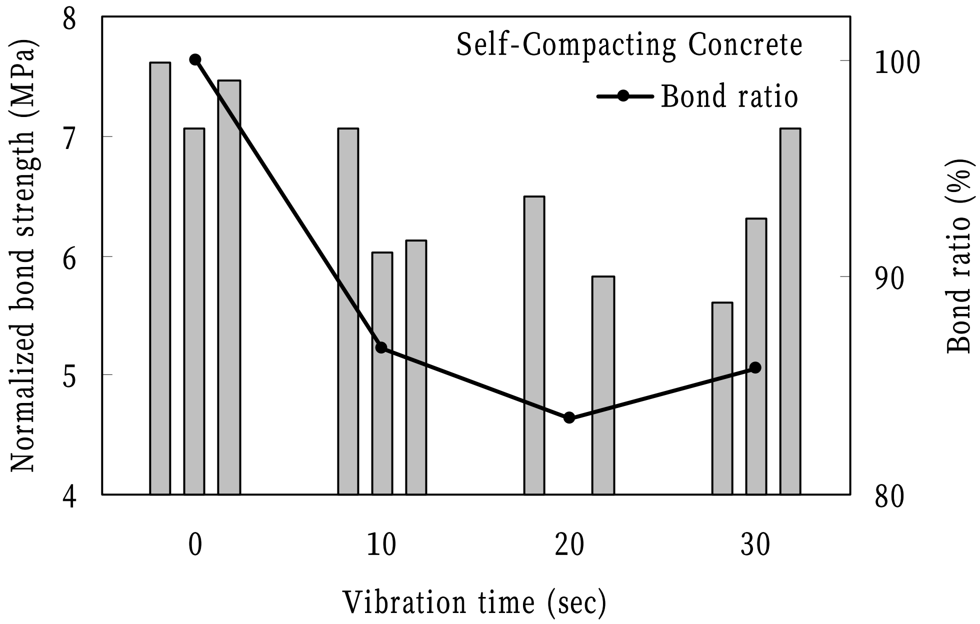


Figure 14 Bond strengths of SCC in various consolidation conditions

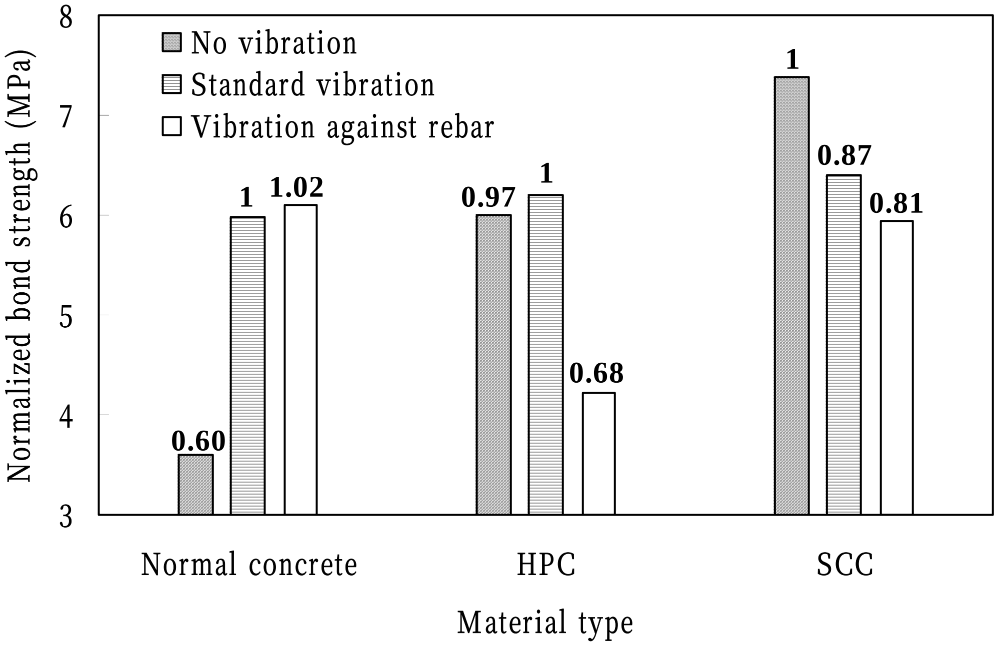


Figure 15 Bond strengths of various concretes under no vibration, standard vibration, and vibration against rebars