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Effect of Recycled Aggregate Quality on the Bond Behavior and Shear Strength of RC Members

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Abstract: During the aggregate crushing process, natural aggregate and clinging mortar from existing concrete will inevitably produce small cracks and weak bonds between the aggregate and the existing cement mortar. The weaknesses of the existing cement mortar, adhered to a natural aggregate, negatively affect the properties of a recycled aggregate concrete, which prevents its application in reinforced concrete (RC) structures. Recycled aggregate can be classified into several categories, according to its physical and mechanical properties. The properties of concrete incorporated with the recycled aggregate of various qualities can be controlled, and the variability in its strength can also be reduced. This study aims to promote the application of recycled aggregate by investigating the effects of recycled aggregate quality (i.e., water absorption and the number of fine particles) classified by the Japanese Industrial Standards (JIS) on material properties, mechanical properties, and shear behavior of RC beams with recycled aggregate.

Keywords: recycled aggregate quality; bond strength; shear behavior; aggregate interlock mechanism; size effect

1. Introduction

Concrete materials have become the second most-consumed type of material in the world [1]. Due to the considerable annual demand for concrete and aggregate, the supply of these materials in the near future is suspect. The global demand for construction aggregates is estimated to increase by 5.2%, annually, to 48.3 billion tons, until 2020. A large percentage of the global aggregate supply (approximately 67%, in 2015) is consumed in Asia-Pacific countries. The sustainable development of these materials relies on the judicious use of natural resources. The use of recycled aggregate from crushed concrete waste, for the production of new concrete, is one alternative offering an effective green solution by prolonging the lifespan of natural aggregate. Although the advantages of recycled aggregate are widely recognized, its applications remain limited. Several researchers have investigated the effects of recycled aggregate on the properties and behavior of concrete. For example, several authors investigated the effect of the parent concrete properties on the properties of recycled aggregate concrete [2,3]. Serifou et al. [4] investigated concrete made with fine and coarse aggregates recycled from fresh concrete waste. Abdullahi et al. [5] investigated the effect of aggregate type on the compressive strength of concrete.

The weaknesses and mortar content of recycled aggregate depend on the type, size, and strength of the natural aggregate, as well as the parent concrete strength, crusher types, and crushing processes.

A parent concrete of a higher strength creates a stronger mortar and a better bond between the mortar and the natural aggregate, leading to improvements in the properties of the recycled aggregate concrete. However, the higher mortar content could have greater negative effects on the recycled aggregate concrete properties. It is extremely difficult to obtain information on the recycled aggregate, parent concrete, and aggregate production from recycling factories because concrete waste is typically obtained from a variety of sources. Therefore, another approach should be developed to more widely understand and control the effects of recycled aggregate quality on concrete properties. Such an approach would expand the application of recycled aggregate concrete in structural concrete members. Zhao et al. [6] proposed the study of stress–strain behavior of the fiber-reinforced plastic (FRP)-confined recycled aggregate concrete. The effects of replacement by recycled coarse aggregate, on the axial and the lateral strain of a concrete cylinder, were examined. The experimental results show that the specimens that use 20% replacement, by a coarse, recycled aggregate, behave similarly to that of normal concrete but specimens that use a 100% replacement show a lower strength and significantly different stress–strain response. Xu et al. [7] investigated the mechanical behaviors of recycled aggregate, under a tri-axial compression of the FRP-confined column; the influence of a recycled aggregate content and its source were also examined.

In the field of civil engineering, concrete is always reinforced with steel rebar, and the bond strength and interacting behaviors between the concrete and steel rebar are among the most important requirements of reinforced concrete (RC) design and construction. The bond behavior of concrete is controlled by the concrete type, rebar arrangement, loading conditions, and construction details [8]. The bonding strength between natural and recycled aggregate concrete and rebar are similar, although the compressive strength exhibits a downward trend with increases in the recycled coarse aggregate replacement ratio [9]. Creazza and Russo [10] presented a model for predicting crack-width on the basis of bond stress, with different reinforcement amounts and concrete strength. It was confirmed that the effect of reinforcement amounts on the crack-width was significant. Thus, the compressive strength alone can no longer be used as the main parameter to estimate the bond strength between the recycled aggregate concrete and the steel rebar. The recycled aggregate has a lower density than natural aggregate, due to the lower density and porous nature of the existing adhered cement mortar.

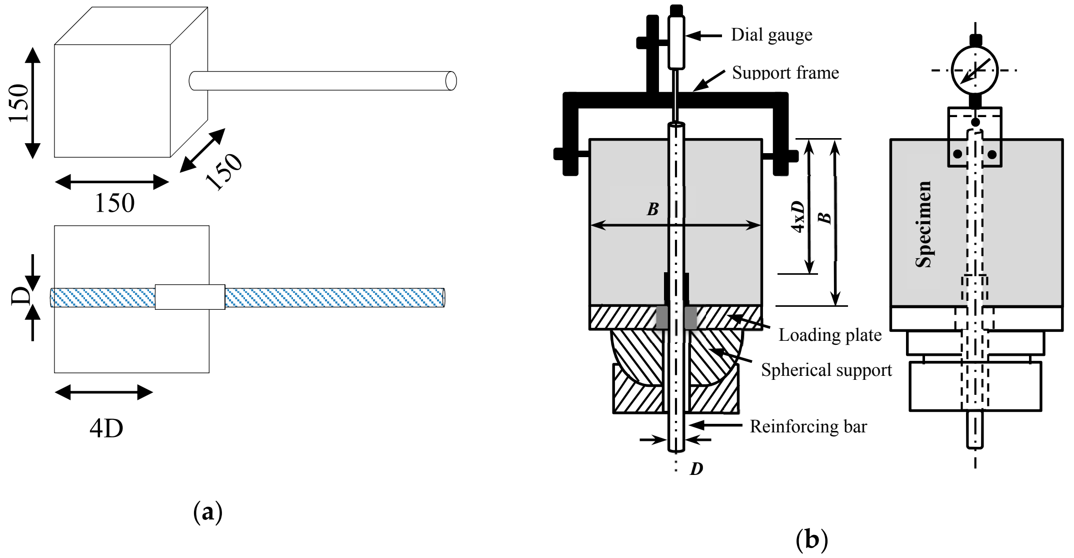
Fathifazl et al. [11] and Kim et al. [12] reported that the shear strength of RC beams with recycled aggregate concrete was lower than that of RC beams with natural aggregate concrete, with the same testing procedure and mix proportions, even though there were no significant differences between the failure modes and the crack patterns. Sato et al. [13] conducted loading tests on RC members using a recycled aggregate to evaluate whether recycled aggregate can be applied to concrete structures. The experimental results showed that the effects of recycled aggregate on the ultimate flexural and ductility capacities were rarely observed because the beams failed in pure flexure or flexure-shear, after the yielding of the tensile reinforcing bars. Therefore, the ultimate flexural strength could be estimated by using conventional structural analysis.

There is limited published experimental data on the structural behavior of RC components that use recycled aggregate. When conducting structural experiments on RC components using recycled aggregate, it is important to consider that recycled aggregate is produced from various RC members of building structures. The application of a recycled aggregate to structural concrete depends on the resulting properties. In this study, to clearly understand the effects of the properties of the recycled aggregate on the structural performance, the quality of the recycled aggregate, classified as high, medium, or low-quality, based on Japanese Industrial Standards (JIS), depending on the water absorption and the number of fine particles, is taken as the main test parameter. The bond behavior between the deformed steel rebar and concrete, and the shear behavior of the RC beams, without shear reinforcement, were experimentally investigated.

2. Experimental Program

2.1. Specimen for Bond Testing

To more thoroughly understand the effects of the recycled aggregate quality on the bond behavior of the interaction between the recycled aggregate concrete and the steel rebar, different water-to-cement ratios (0.30, 0.45, 0.60, and 0.75) and different diameters of the deformed steel rebar (13 and 19 mm) were considered. Due to the large variation within the specimens, the specimens were cast with 13-mm or 19-mm-diameter deformed steel rebar for the pull-out tests, to understand the failure behavior of the recycled aggregate concrete bond strength at the ultimate load and in the post-peak region. The specimens for the bond tests were developed, such that bond stresses for different steel diameters could be compared by maintaining the embedment-to-steel diameter ratio, following the procedure presented by Yamao et al. [14] and Hong et al. [15]. They reported that the bond stress of specimens with short embedment depths exhibits a higher strength than those with long embedment depths, for a given steel diameter. The concrete specimens, made with natural and recycled aggregate concrete, for the pull-out tests, were cubic in shape, with a side length of 150 mm. The concrete was poured into the mold, as shown in Figure 1a, to keep the rebar stable and at the correct position, in the RC beam.



(a)

(b)

Figure 1. Specimen installation for the pull-out test using the Japan Society of Civil Engineers (JSCE). (**a**) Dimension of specimen and (**b**) specimen installation.

The 13- and 19-mm deformed bars were embedded in the concrete, with a length that was four times the steel diameter, and the remaining portion of the bars was covered by plastic piping to prevent the steel surface from contacting the concrete. This short embedment length allowed a uniform bond-stress distribution to be assumed. Sixty-four specimens were prepared for the pull-out tests of the steel rebar embedded in the natural and recycled aggregate concrete. For each natural (N) aggregate concrete and concrete with high-quality (H), medium-quality (M), and low-quality (L) recycled coarse aggregate replacement, three specimens were cast with a 13-mm-diameter deformed steel rebar and one specimen was cast with a 19-mm-diameter deformed steel rebar to consider the effects of the steel bar diameter on the bond behavior. The tensile load provided by the hydraulic universal testing machine was recorded automatically. The loading rate for the deformed rebar with diameters of 13 and 19 mm was varied from 2 to 6.6 MPa/min. Following the experimental procedure specified by JSCE-G 503-1998 "Bond strength testing of reinforcement and concrete by pull-put" [16], the vertical slip of the steel rebar (i.e., the relative displacement of the steel rebar and the concrete specimen) was measured using a dial gauge, installed at the top of the concrete specimen, as shown in Figure 1b.

2.2. Specimens for Shear Testing

The shear behavior of the RC beams using a recycled aggregate concrete was investigated using two groups of RC rectangular beams without shear reinforcement. The details of the specimen are shown in Figure 2. The RC beams were subjected to four-point bending tests. All of the beam specimens were designed such that they would fail in diagonal shear failure and not shear compression failure. The different-sized beam specimens were designed to consider the fact that the shear resistance of RC beams typically decreases with an increase in the effective depth of the RC beam [17]. For larger beams, the aggregate particle size is relatively smaller than the beam cross-section. Thus, the aggregate interlocking mechanism is not effective in improving the shear resistance in larger beams.

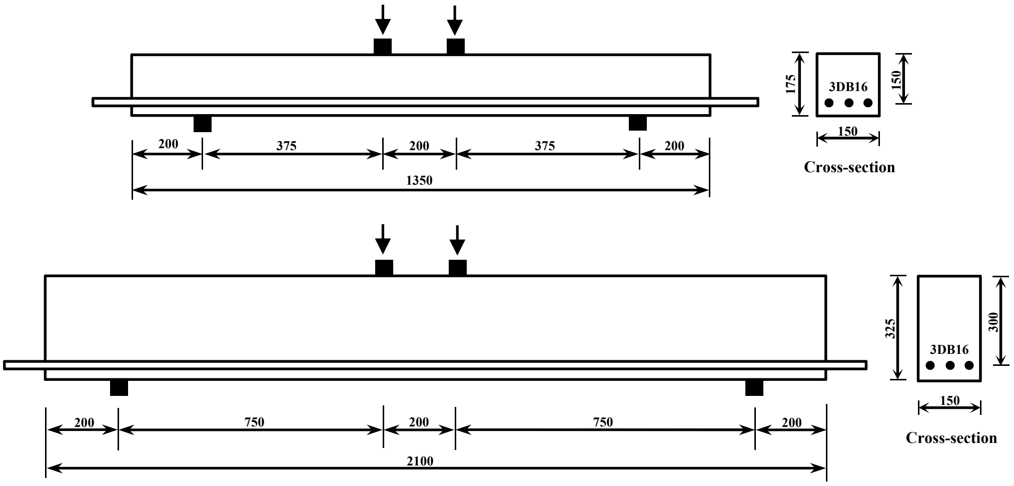


Figure 2. Specimen dimensions and loading points for the shear testing (unit: mm).

Each group of specimens for the shear strength test had four beam specimens with different coarse aggregate replacements: Natural aggregate and high-, medium-, and low-quality recycled aggregate. The details of the specimens are provided in Table 1. The suffixes B60 and S60 represent large and small specimens, respectively, with water-to-cement ratios of 0.60. The concrete cover depth of all specimens was 25 mm, and the cross-sectional area of the longitudinal rebar was 596 mm^2, enough to prevent flexural failure. The beam length was extended by 200 mm at each end to prevent tensile bond failure of the steel rebar. The shear span-to-effective depth ratio (a/d) was kept constant at 2.5 for both the large and small specimens.

Table 1. Details of the specimen for the shear tests. N: natural aggregate concrete; H: high-quality; M: medium-quality; L: low-quality (L).

Specimen	b (mm)	d (mm)	h (mm)	a (mm)	Pure Bending (mm)	Length (mm)	a/d	ρ (%)
NS60	150	150	175	375	200	2100	2.5	2.65
HS60								
MS60								
LS60								
NB60		300	325	750		1350		1.32
HB60								
MB60								
LB60								

Two strain gauges were attached to the steel rebar before casting the concrete to confirm that the yielding of steel rebar would not occur. Two other strain gauges were attached to the concrete, subjected to a compression zone, at the mid-span, to estimate the change in the neutral axis and the concrete crushing. Three dial gauges were used to measure the beam deflections; the dial gauges were located at the (1) mid-span of the beam, (2) left mid-shear span, and (3) right mid-shear span. During the experiment, the load corresponding to the first crack expected to occur at the pure bending region was measured. Then, the first diagonal crack in the shear span region, after the appearance of the flexural crack, was also recorded.

2.3. Material Properties

This study used a natural coarse aggregate and three qualities of the recycled coarse aggregate, with particle sizes ranging from 5 to 20 mm. The relationship between the cumulative percentage passing and the particle sizes for the different aggregate qualities is shown in Figure 3. Natural sand was used as the fine aggregate for all concrete mixes. The detailed physical properties of the coarse aggregates are provided in Table 2. Although the densities of the natural and high-quality recycled coarse aggregate are highly similar, the water absorption of the high-quality recycled aggregate is slightly higher than that of the natural aggregate. The cross-section of the coarse aggregate is shown in Figure 4.

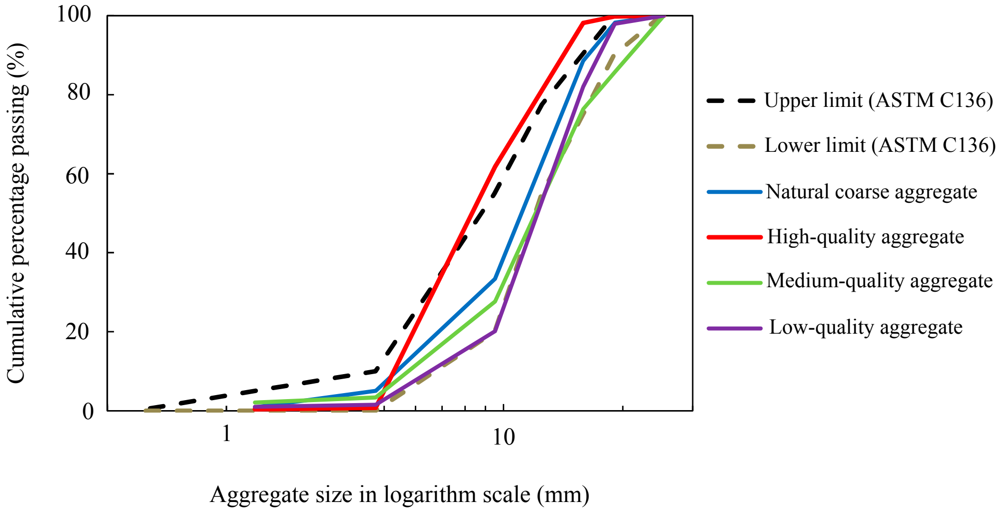


Figure 3. Size distributions of the coarse natural and recycled aggregates.


(**a**) (**b**) (**c**) (**d**)

Figure 4. Cross-sections of the natural and recycled coarse aggregates. (**a**) Natural coarse aggregate; (**b**) high-quality recycled coarse aggregate; (**c**) medium-quality recycled coarse aggregate; (**d**) low-quality recycled coarse aggregate.

Table 2. Physical properties of the coarse aggregate. SSD: Saturated-surface dry; OD: Oven-dry.

Aggregate	Notation	SSD Specific Gravity	OD Specific Gravity	Water Absorption %	Moisture Content %
Natural fine aggregate	NF	2.55	2.47	2.14	3.47
Natural coarse aggregate	N	2.63	2.60	1.02	1.00
Recycled coarse aggregate	H	2.63	2.60	1.16	0.70
	M	2.55	2.47	3.06	2.80
	L	2.41	2.27	5.92	4.19

The texture of the natural aggregate is highly similar to that of coarse basalt aggregate, whereas the high-quality recycled aggregate is uniform and similar to marble stone. The medium- and low-quality recycled aggregates are highly similar to the natural and high-quality recycled aggregates, respectively. The main difference between them is the amount of old mortar that is still adhered to the particles. The strength of the recycled aggregate concrete is controlled by (1) the aggregate strength, (2) the bond between the aggregate and adhered old mortar, (3) the bond between the aggregate and the new mortar, (4) the bond between the new and the old mortar, and (5) the new mortar strength. The low-quality recycled aggregate could be easily identified as having the largest amount of adhered old mortar. The recycled aggregates used in this experiment were classified by the JIS, according to their properties, as shown in Table 3.

Table 3. Classification of the recycled aggregate based on the Japanese Industrial Standards (JIS).

Properties	**Natural Aggregate**	**Recycled Aggregate**		
		High-Quality	**Medium-Quality**	**Low-Quality**
	JIS A5308	**JIS A5021**	**JIS A5022**	**JIS A5023**
		Coarse aggregate		
Oven-dry density (g/cm3)	$\geq$2.5	$\geq$2.5	$\geq$2.3	–
Water absorption (%)	$\leq$3.0	$\leq$3.0	$\leq$5.0	$\leq$7.0
Solid content (%)	–	$\geq$55	$\geq$55	–
Amount of fine particle (%)	$\leq$1.0	$\leq$1.0	$\leq$1.5	$\leq$2.0
Chloride amount (%)		$\leq$0.04	$\leq$0.04	$\leq$0.04

3. Experimental Results

3.1. Properties of Fresh Concrete

For the bond strength tests, the slump test of the natural and recycled aggregate concrete with different water-to-cement ratios is shown in Figure 5. There were no noticeable differences in the slump among the different recycled aggregate qualities, for different water-to-cement ratios, even though there was an approximate 1% difference in their air content. However, the concrete with a water-to-cement ratio of 0.30 had a notably low slump. A water reduction agent must be used to improve the workability of both the natural and the recycled aggregate concrete. Therefore, the loss of workability related to the higher water absorption of recycled aggregate could be neglected when recycled aggregates were presoaked. To illustrate the shear strength test, the slump and air content test results are shown in Figure 6. The slump decreased steadily, based on the quality of the recycled aggregate. The slump of the concrete with a low-quality recycled aggregate was 25% lower than for the concrete with a natural aggregate for the large-beam specimens. In contrast, the air content of the concrete with a low-quality recycled aggregate was 17% higher than that of the natural concrete. There was no a significant difference in the air content or the slump for the small beams, except that LS60 had the lowest slump of 18 cm. The slumps of the different types of fresh concrete were consistently higher than the estimated value of 12 cm, even though the air content was lower than the target value of 6%. Thus, the concrete was not sufficiently solid to maintain the air content in the concrete.

3.2. Properties of Hardened Concrete

3.2.1. Compressive Strength

The compressive strength of the hardened concrete with different water-to-cement ratios is shown in Figure 7. The compressive strength of concrete did not depend on the quality of the recycled aggregate for the lower-strength concrete, and the differences became more dramatic as the concrete strength increased. For the lower-strength concrete, the ultimate strength might not be governed by the strength of the aggregate or the cement mortar. The average compressive strength increased from 30% to 50% with a 15% decrease in the water-to-cement ratio, regardless of the recycled aggregate quality.

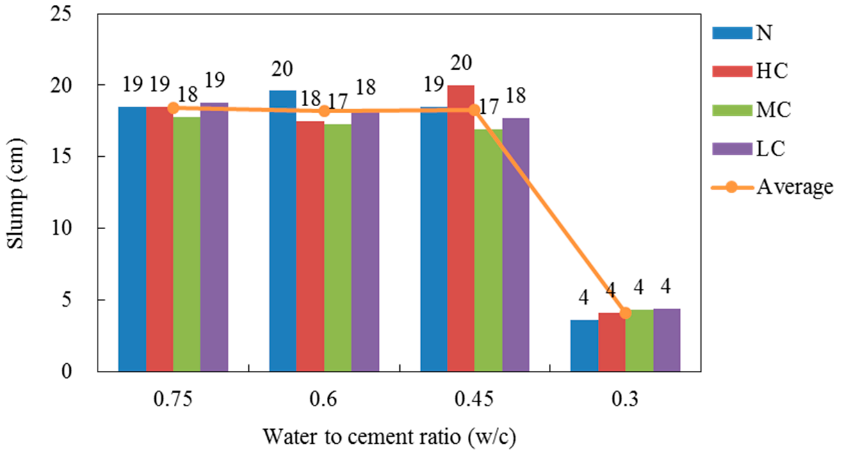


Figure 5. Slump of fresh concrete with different water-to-cement ratios. N: natural aggregate concrete; HC: high-quality recycled aggregate concrete; MC: medium-quality recycled aggregate concrete; LC: low-quality recycled aggregate concrete.

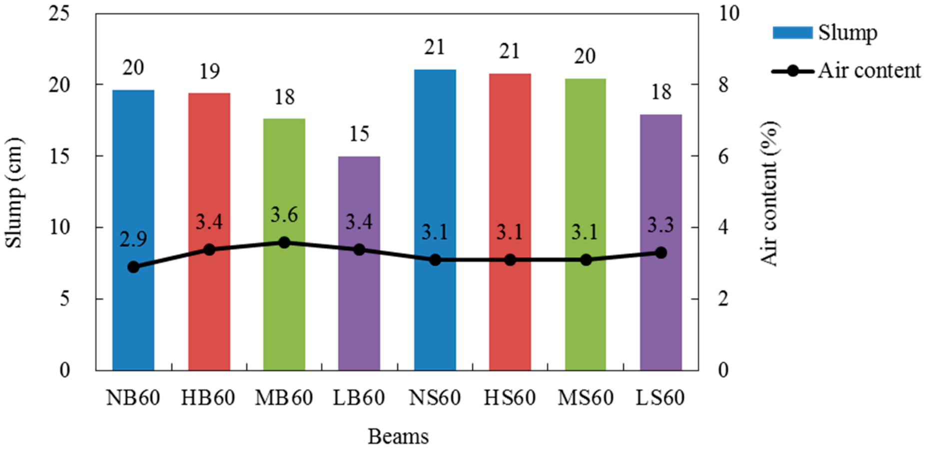


Figure 6. Slump and air content of fresh concrete.

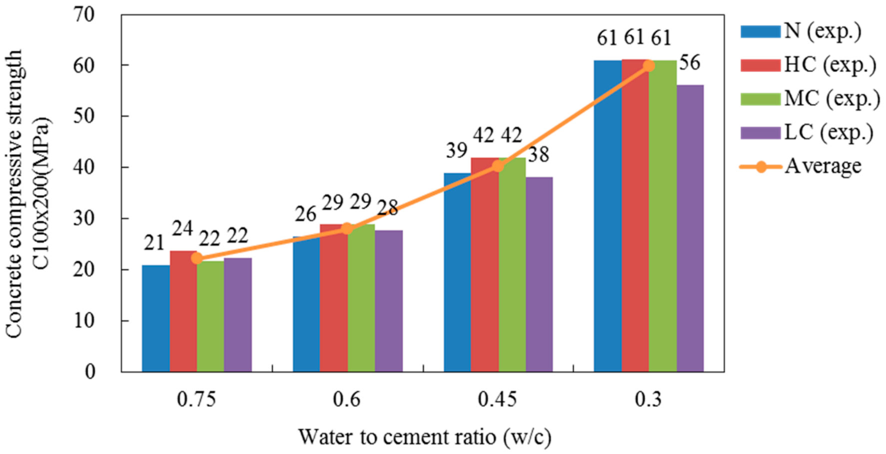


Figure 7. Compressive strengths under different water-to-cement ratios.

3.2.2. Mortar Compressive Strength

The compressive strength of the mortar with different water-to-cement ratios is shown in Figure 8. The compressive strength of the mortar exhibited the same trend as the concrete compressive strength. However, the mortar compressive strength was higher than the concrete compressive strength, regardless of the aggregate type. Viso et al. [18] found that the size effects of the cylinder compressive strength of the cylinder specimens were negligible. Thus, the compressive strength of all concrete specimens was governed by the aggregate strength, the bond strength between the aggregate and mortar, or the bond strength between the old and new mortar. An example is the case of the natural aggregate. Although the mortar compressive strength of the natural aggregate was higher, the compressive strength of the natural aggregate concrete was highly similar to the strength of the low-quality recycled aggregate concrete.

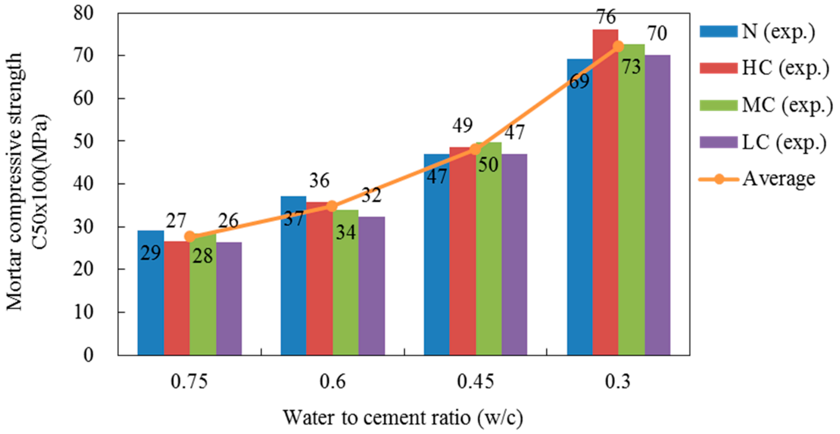


Figure 8. Compressive strength of mortar with different water-to-cement ratios.

3.2.3. Split Tensile Strength

The effects of the recycled aggregate quality on the concrete tensile strength with different water-to-cement ratios are shown in Figure 9. Overall, the split tensile strength for each concrete specimen increased with decreases in the water-to-cement ratio. The compressive strength of the mortar and concrete specimens exhibited the same trend. However, the split tensile strength of the natural aggregate concrete was highly similar to that of the low-quality recycled aggregate concrete. The exception was the concrete with a water-to-cement ratio of 0.60, where the split tensile strength of the natural aggregate concrete was the highest in the group but with the lowest compressive strength. The difference in the split tensile strength could be better understood by considering the compressive strength of the mortar.

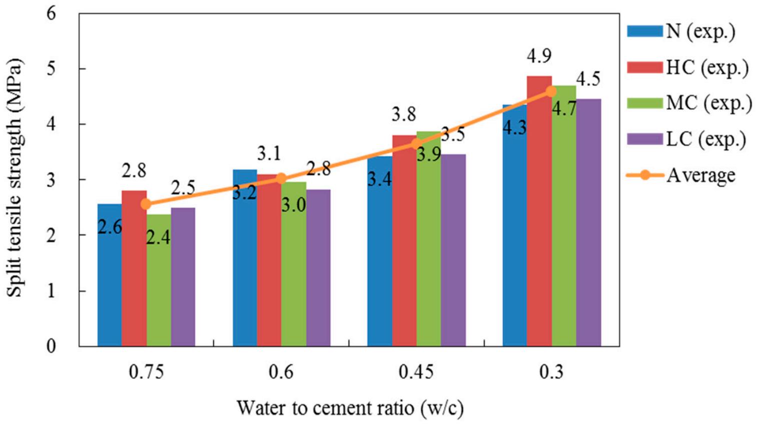


Figure 9. Split tensile strength of concrete with different water-to-cement ratios.

3.2.4. Elastic Modulus

- Static Modulus

The experimental results of the static elastic modulus for the concrete are shown in Figure 10. Although the compressive strengths of the natural and the low-quality recycled aggregate concrete were highly similar, the static elastic modulus of the natural aggregate concrete was higher than that of the low-quality recycled aggregate concrete and even higher than those of the high- and medium-quality recycled aggregate concrete, except for the case with a water-to-cement ratio of 0.60. This difference in trend could be due to a lower stiffness of the recycled aggregate resulting from the relatively weak adhesion of the adhered old mortar.

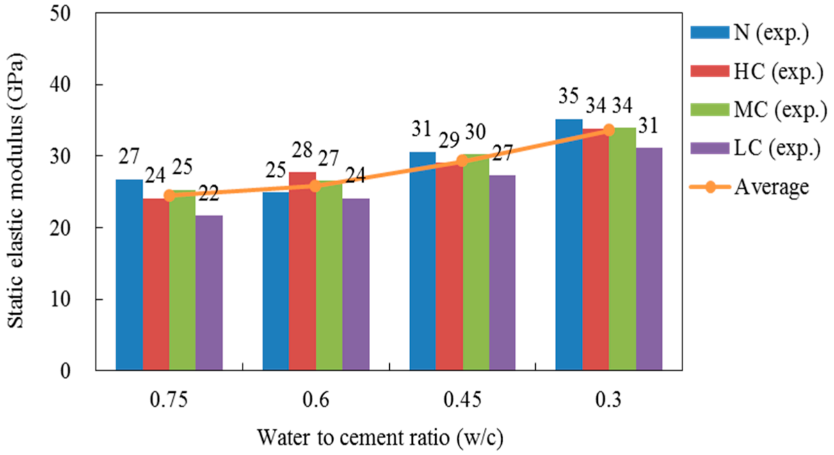


Figure 10. Static modulus at 28 days with different water-to-cement ratios.

- Dynamic Modulus

The dynamic elastic moduli of the concrete measured with the resonance vibration method are shown in Figure 11. The slope of the curve was largely flat when the water-to-cement ratio changed from 0.60 to 0.45. Compared to the natural aggregate concrete, the dynamic modulus of the concrete with a low-quality recycled fine aggregate was 24.3%, 20.5%, 17.5%, and 15.6% lower for the different water-to-cement ratios, indicating that the difference between the dynamic modulus of the natural and low-quality recycled aggregate concrete decreased with a decrease in the water-to-cement ratio or with an increase in the compressive strength. The dynamic modulus of the low-quality recycled coarse aggregate concrete was approximately 8 GPa lower than that of the natural aggregate concrete.

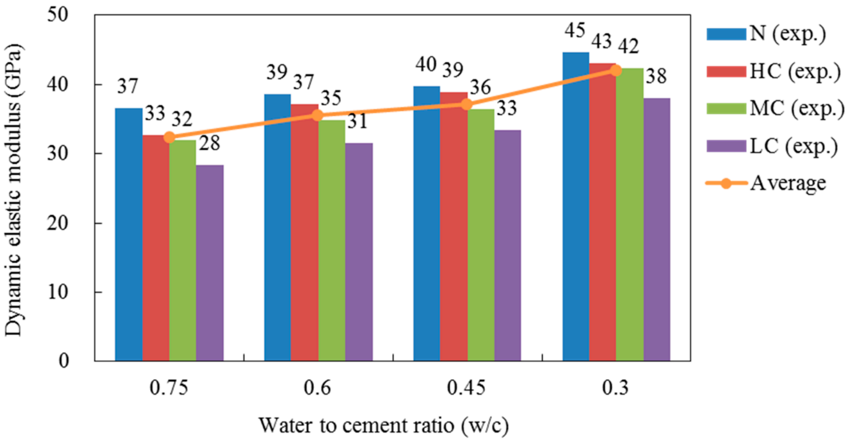


Figure 11. Dynamic modulus of concrete at 28 days with different water-to-cement ratios.

3.2.5. Drying Shrinkage

The results of the drying shrinkage of the natural and recycled aggregate concrete with different water-to-cement ratios are illustrated in Figure 12. The variation in temperature and humidity between specimens was reduced because the four different-quality aggregate concrete and the natural aggregate concrete were cast and cured at the same time. It could be concluded that the ultimate shrinkage of both the natural and recycled aggregate concrete decreased as the water-to-cement ratio decreased. The same trend occurred for the mechanical and elastic behavior of the concretes made of the recycled-concrete coarse aggregates. The drying shrinkage of the low-quality recycled coarse aggregate concrete was the highest, whereas the shrinkage of the concrete with the medium- and high-quality recycled aggregate were highly similar in terms of their water-to-cement ratios—0.75 and 0.60. The increase in drying shrinkage could be explained by the adhered old cement mortar contributing to an increase in the volume of the paste (old + new), as proposed by Tavakoli et al. [19] and Kou et al. [20]. For the case of a water-to-cement ratio of 0.60, the drying shrinkages of the low-, medium-, and high-quality recycled aggregate were 902, 749, and 724 µm/m, which were 39.2%, 15.6%, and 11.7% higher, respectively, compared to that of the natural aggregate concrete (648 µm/m) over the same period. The drying shrinkage for specimen HC60 was slightly higher than that of concrete made by 50% high-quality recycled coarse aggregate replacement and a water-to-cement ratio of 0.64, after 56 weeks, as determined by Morohashi et al. [21]. For the case of a water-to-cement ratio of 0.45, the quality of the recycled aggregate had nearly no effect on the drying shrinkage of concrete. However, for the higher-strength concrete, the drying shrinkage of the low-quality recycled aggregate concrete was lower than that of the high- and medium-quality recycled aggregate concrete but higher than that of the natural aggregate concrete.

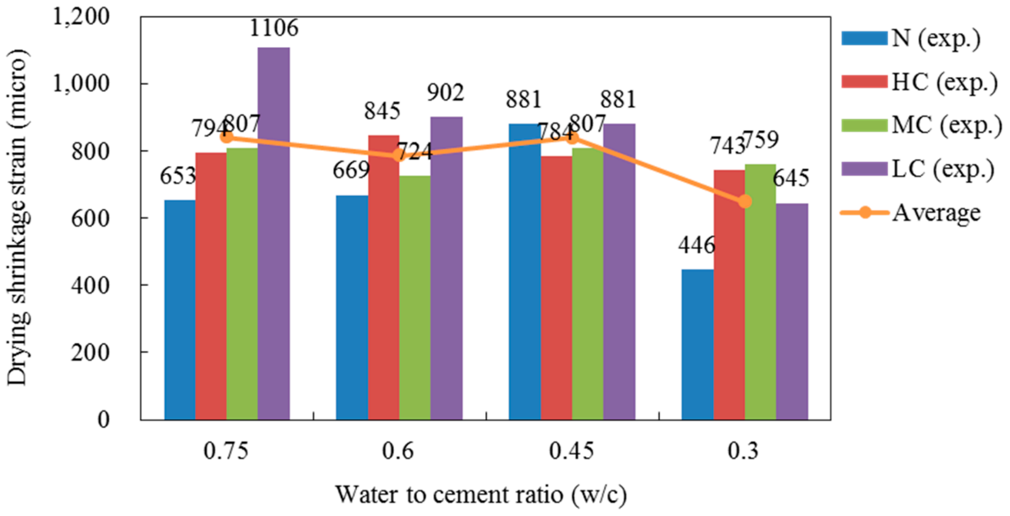


Figure 12. Ultimate drying shrinkage strain of concrete with different water-to-cement ratios.

3.3. Bond Behavior

According to the experimental results of the pull-out test, the bond strength could be expressed as

$$\tau_{\max} = \frac{P_{\max}}{\pi d l_a} \tag{1}$$

where $\tau_{\max}$ was the peak bond stress between the concrete and steel rebar (MPa), $P_{\max}$ was the peak load indicated by the universal testing machine (N), d was the diameter of the steel rebar (mm), and l_a was the embedment length of the steel rebar (mm) and was equal to four times the steel diameter.

3.3.1. Effect of the Material Properties on the Bond Strength

The bond strength between the concrete and deformed steel rebar for different water-to-cement ratios and for 13 and 19 mm diameters are illustrated in Figure 13. The bond strength between the concrete and deformed bars tend to increase with decreases in the water-to-cement ratio. Unlike the compressive and split tensile strength of the concrete, when the water-to-cement ratio decreased from 0.6 to 0.45, the bond strength between the concrete and the deformed bars appeared to be constant. This trend could be explained by the increase in drying shrinkage having a tendency to decrease with the water-to-cement ratio and resulted in a gentler slope of the dynamic elastic modulus. The bond strengths between the concrete and the 13- and 19-mm-diameter deformed bars had nearly the same ultimate value and trends, indicating that the steel diameter had no effect on the bond strength between the concrete and steel rebar, when the embedded length was in proportion to the steel diameter (four times the steel diameter). In addition, the difference in the bond strengths of concrete with different types of coarse aggregate replacement was consistent with the differences in other material properties, such as the concrete compressive strength, split tensile strength, and static elastic modulus. Compared to the recycled aggregate replacement ratio, the recycled aggregate quality had a greater effect on the bond strength between the steel rebar and the concrete with the recycled coarse aggregate replacement, even though the bond strength between the deformed bars and the recycled aggregate concrete were comparable to that of the natural aggregate concrete, due to the mechanism of the rib of the deformed bars. For example, the bond strength of the concrete with the low-quality recycled coarse aggregate was always the lowest (up to a 24.5% reduction in bond strength for the worst case). However, the attenuation in strength could be ignored for the high- and medium-quality recycled aggregate concretes. In some cases, the bond strength of the concrete with the high- and medium-quality recycled coarse aggregate replacement was higher than the bond strength of the natural aggregate concrete (8.34% and 5.27% higher for the high-quality and the five medium-quality recycled coarse aggregate concrete, respectively, with a water-to-cement ratio of 0.30).

3.3.2. Bond Stress-Slip Relation

There was a clear difference in the bond strength between the deformed steel rebar and concrete made with natural and recycled aggregates of different qualities.

With the 13-mm-diameter steel rebar, the majority of the concrete specimens did not fail at the ultimate load, and the post-peak behavior of the bond stress-slip curve could be observed. The average bond stress–strain relationships between the steel rebar and concrete, made with different water-to-cement ratios are plotted in Figure 14a–d. The bond behavior between the steel rebar and the concrete with natural and recycled aggregate and with different water-to-cement ratios are highly similar, except for the concrete with a water-to-cement ratio of 0.30. Although the ultimate bond strengths of the HC30 and the MC30 specimens were higher than that of the N30, the bond stresses of the HC30 and MC30 specimens decreased rapidly in the post-peak region and became lower than that of N30. In contrast, the ultimate bond strength of LC30 was the lowest but became the largest in the post-peak region. When the water-to-cement ratio decreased, the stiffness in the elastic region tended to increase, resulting in a higher ultimate bond strength. The adhesive strength between the concrete and steel rebar also increased with an increase in the water-to-cement ratio, but the magnitude was small, compared to the anchorage mechanism of the rib of the deformed bars.

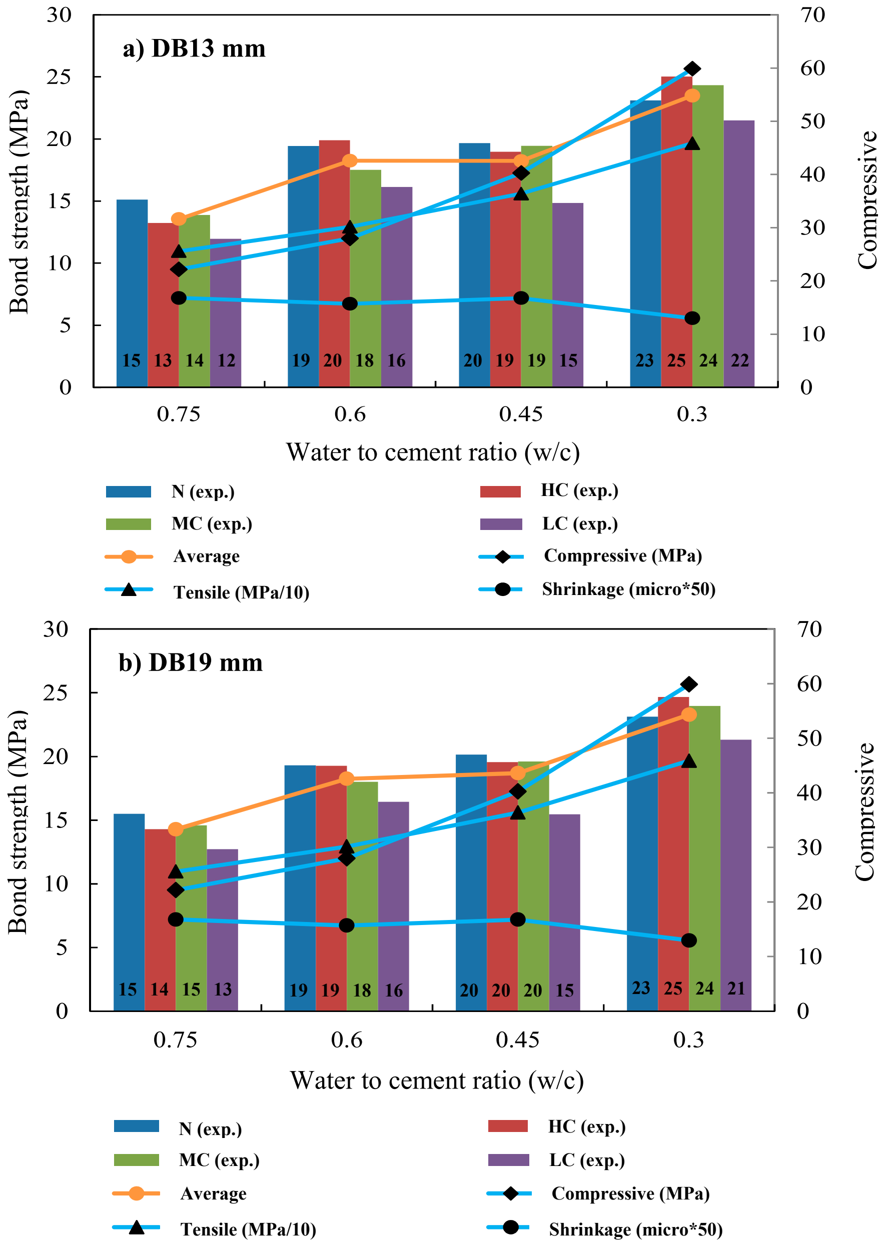


Figure 13. Bond strength between the steel rebar and concrete with different water-to-cement ratios and bar diameters. (**a**) DB13 mm and (**b**) DB19 mm.

With the 19-mm-diameter steel rebar, all of the specimens broke at the maximum tensile load. Therefore, the post-peak behavior of the bond between the concrete and the steel rebar could not be obtained for this diameter. The experimental results are shown in Figure 15a–d. The slope of the bond stress-slip curve was steeper for the lower water-to-cement ratios. The slip value of specimens with the low-quality recycled aggregate was larger, and a clear difference could be observed for the case when the water-to-cement ratio was 0.45. However, although the bond strength of the specimens with a water-to-cement ratio of 0.45 was nearly the same as that of the specimens with a water-to-cement ratio of 0.60, there was no significant improvement in strength.

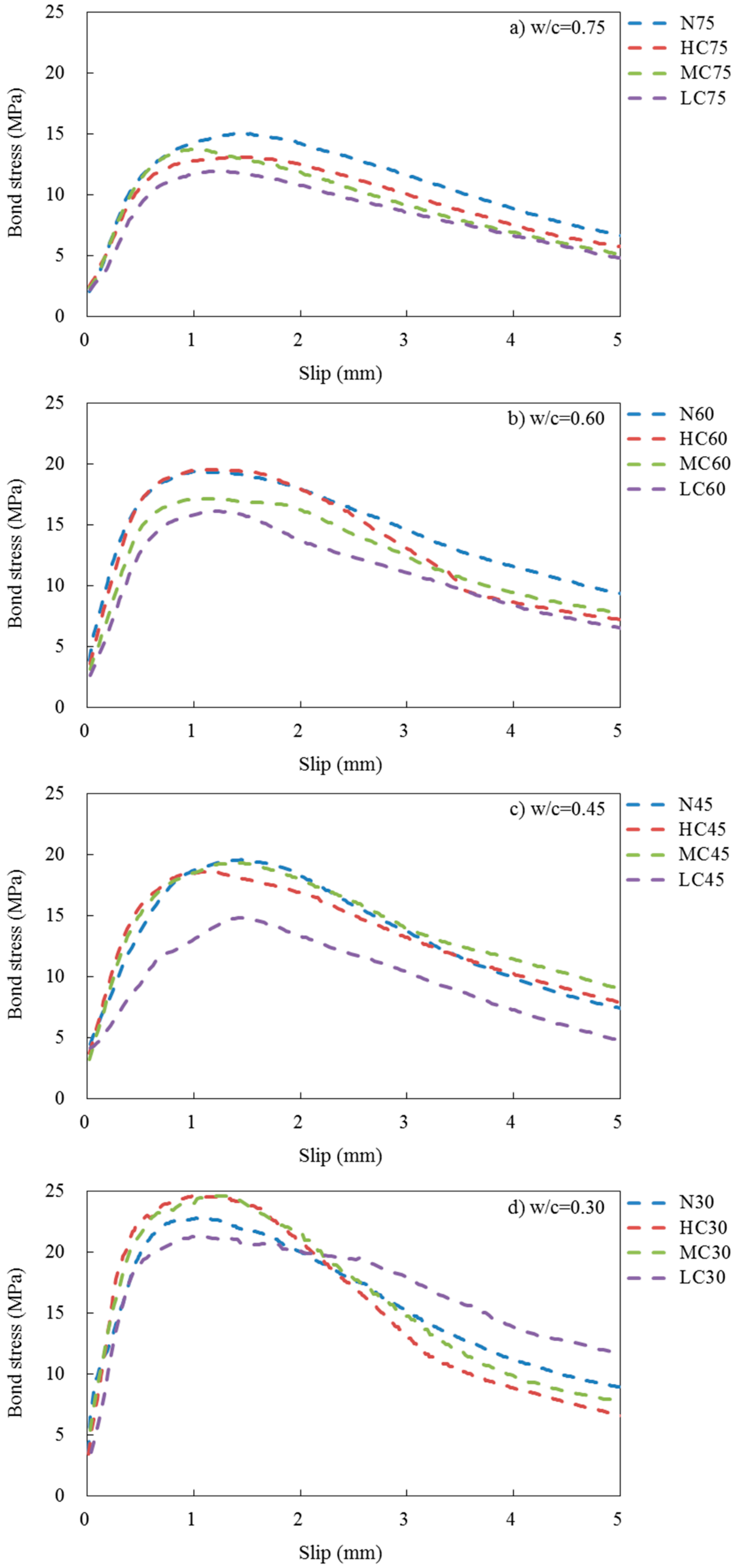


Figure 14. Bond stress-slip relationship of the concrete with a 13-mm-diameter steel rebar with different water-to-cement ratios. (**a**) For w/c = 0.75; (**b**) for w/c = 0.60; (**c**) for w/c = 0.45; (**d**) for w/c = 0.30.

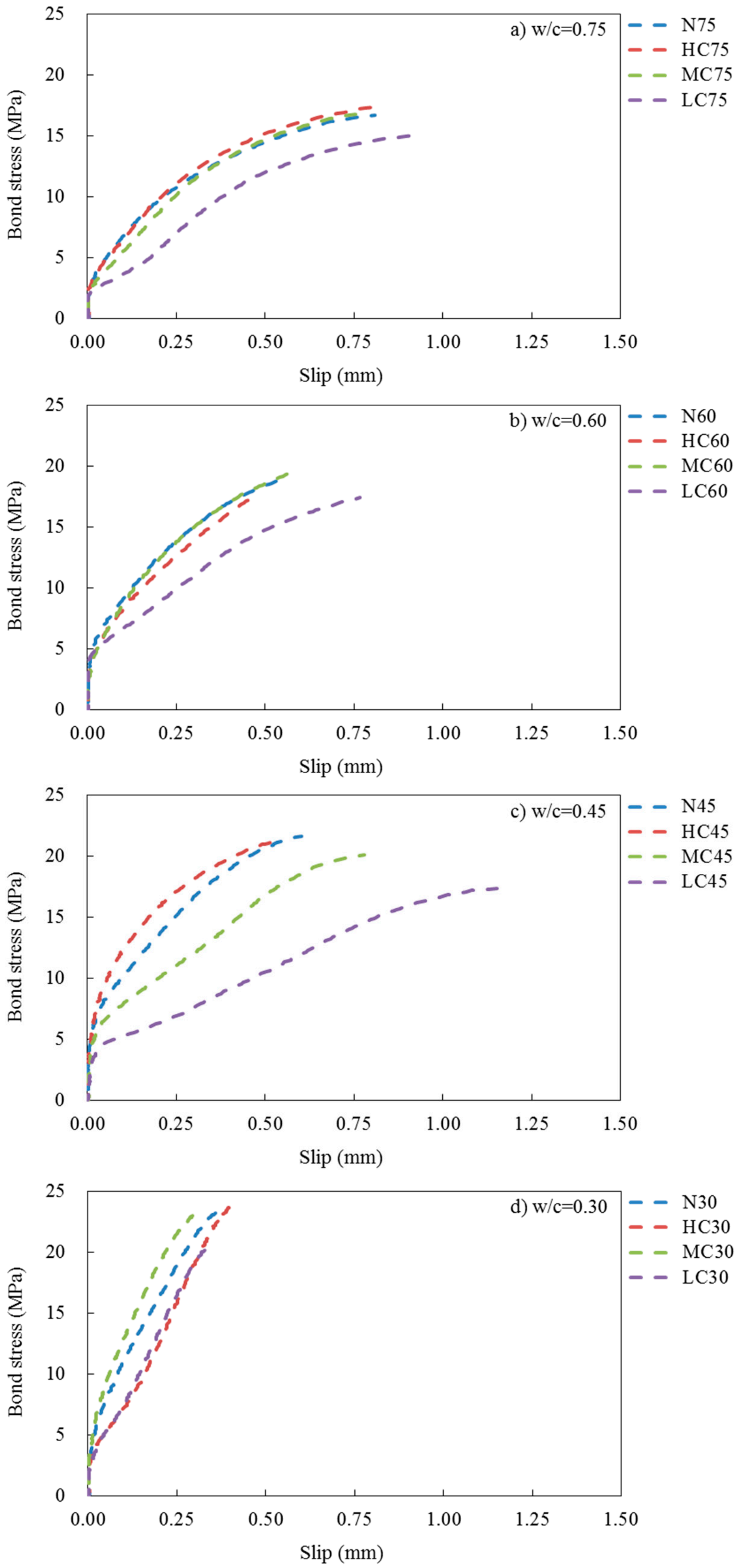


Figure 15. Bond stress-slip relationship of the concrete with a 19-mm-diameter steel rebar with different water-to-cement ratios. (**a**) For w/c = 0.75; (**b**) for w/c = 0.60; (**c**) for w/c = 0.45; (**d**) for w/c = 0.30.

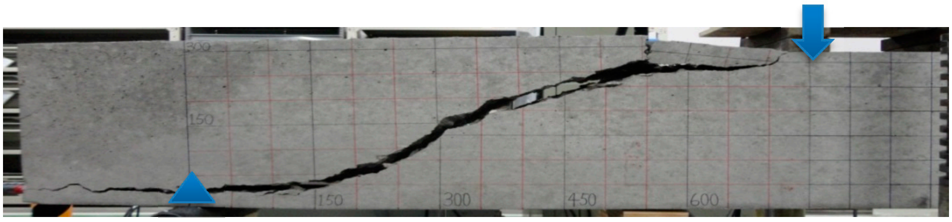
3.4. Shear Behavior

3.4.1. Shear Failure Mechanism

All of the beam specimens hade similar failure modes, exhibiting an initial flexural crack mainly in the pure bending region and subsequent flexural cracks, away from the middle span. As the load increased, the flexural cracks extended into the diagonal cracks within the shear span and typically at the mid-height of the beam. After the formation of large diagonal cracks, the load dropped slightly and the deflection increased considerably. Then, brittle failure occurred, which was consistent with the literature. Fonteboa et al. [22] reported that the shear failure of the RC beams, without shear reinforcement was extremely brittle, and the final failure occurred after the formation of a large diagonal crack. Table 4 compares the experimental load of the large and small RC beams at the occurrence of the first crack, the first diagonal crack, the first peak, and the final peak. The failure modes of the large and small RC beams are shown in Figures 16 and 17, respectively. The loads at which the first large diagonal crack occurred for the RC beams with different recycled aggregate qualities are shown in Figure 16. Load-deflection relationships of the large and small RC beams were illustrated in Figures 18 and 19, respectively. For the small RC beam, the loads at which the first large diagonal crack occurred for NS60, HS60, MS60, and LS60 are 79.1, 71.7, 72.6, and 60 kN, respectively, corresponding to the load-deflection relationship of the small RC beams, as illustrated in Figure 19. The shear behavior of the RC beams with natural and recycled aggregate concrete was highly similar. There are no significant differences between the failure modes, cracking patterns, or shear performance of the RC beams, using the natural or recycled aggregate concrete. The final beam failure due to shear occurred after the formation of a large diagonal crack, except for the beam NB60. Immediately before reaching the maximum shear load, several beam specimens exhibited several vertical cracks that form at the beam top and/or in the shear compression zone.

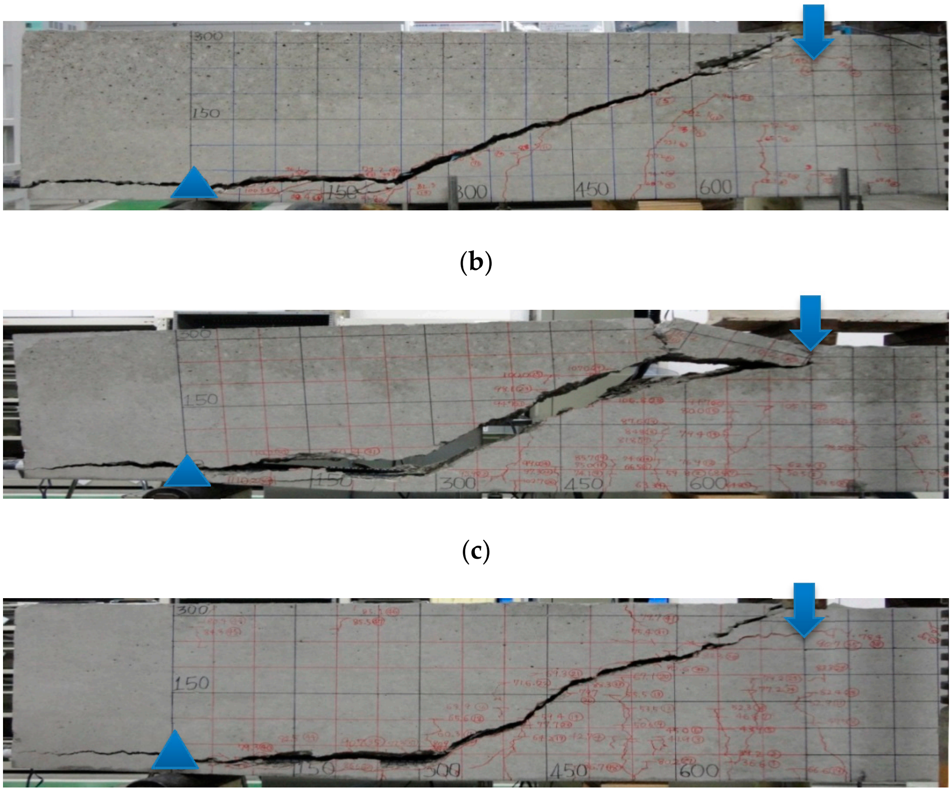
Table 4. Comparison of the experimental load of the reinforced concrete (RC) beam shear testing.

Notation	Experimental Load (kN)			
	First Crack	First Diagonal Crack	First Peak	Final Peak
NB60	70	90	91	93
HB60	50	68	101	102
MB60	51	64	87	110
LB60	30	50	84	99
NS60	43	54	79	103
HS60	38	51	72	88
MS60	29	45	-	73
LS60	22	53	60	75



(**a**)

Figure 16. *Cont.*

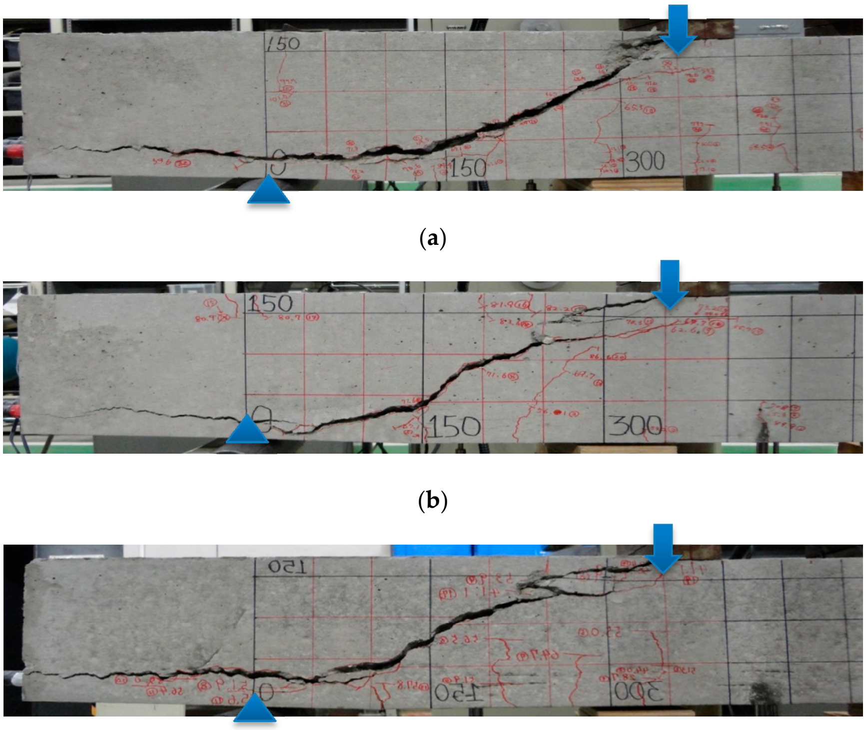


(**b**)

(**c**)

(**d**)

Figure 16. Failure mode of the large reinforced concrete (RC) beams. (**a**) Beam NB60; (**b**) beam HB60; (**c**) beam MB60; and (**d**) beam LB60.

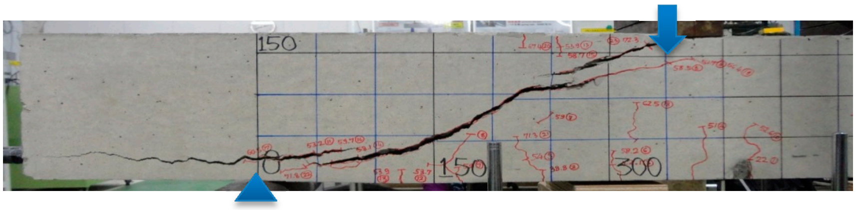


(**a**)

(**b**)

(**c**)

Figure 17. *Cont.*



(**d**)

Figure 17. Failure mode of the small RC beams. (**a**) Beam NS60; (**b**) beam HS60; (**c**) beam MS60; and (**d**) beam LS60.

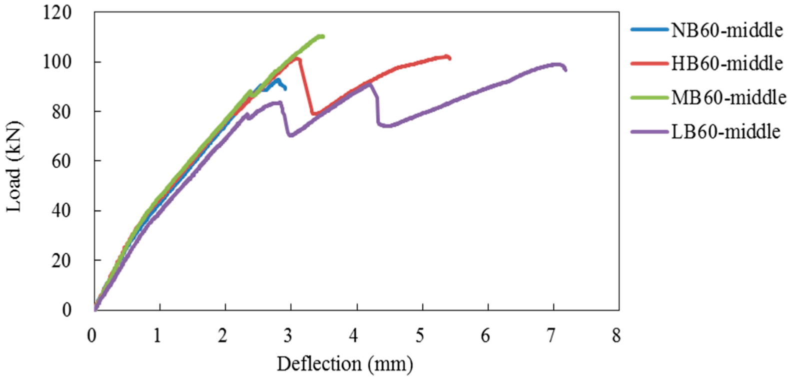


Figure 18. Load-deflection relationship for the large RC beams.

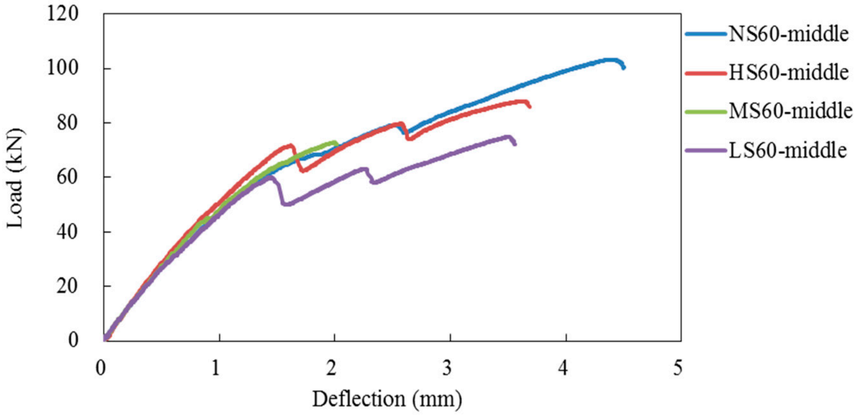


Figure 19. Load-deflection relationship for the small RC beams.

3.4.2. Effect of the Material Properties on the Shear Behavior

The ultimate loads of the shear strength of the RC beams from the experiment are shown in Figure 20 along with their material properties, including (1) the concrete compressive strength from the cylinder specimen (100 mm in diameter and 200 mm in height), (2) the mortar compressive strength from the cylinder specimen (50 mm in diameter and 100 mm in height), and (3) the static and (4) dynamic elastic moduli of the concrete. The total maximum shear strength of the large beams, NB60, HB60, MB60, and LB60, was 93, 102, 110, and 99 kN, respectively. The total maximum shear strengths of all of the large beams, using the recycled aggregate, were higher than that of the NB60 natural aggregate concrete beam, without any attenuation in the observed shear strength. In addition, the shear strength of MB60 was the highest among the group and 7.8% higher than that of HB60. This high shear strength could be due to the 4% and 4.9% higher compressive strengths of the concrete and mortar, respectively, compared to those of HB60. The concrete compressive strength of HB60 was 32 MPa, 6.2% higher than that of NB60 at 30.2 MPa, even though the compressive strength of the NB60 mortar was slightly higher. The natural aggregate had a relatively smooth surface and round shape, which weakened the bond between the cement matrix and the aggregate. For the small beams, the beam width was kept constant at 150 mm, and the effective depth decreased. The influence of the recycled aggregate could be clearly observed in the small beams, even though the concrete compressive strengths of HS60, MS60, and LS60 were 12.4%, 12.6%, and 5.7% higher than that of NS60, respectively.

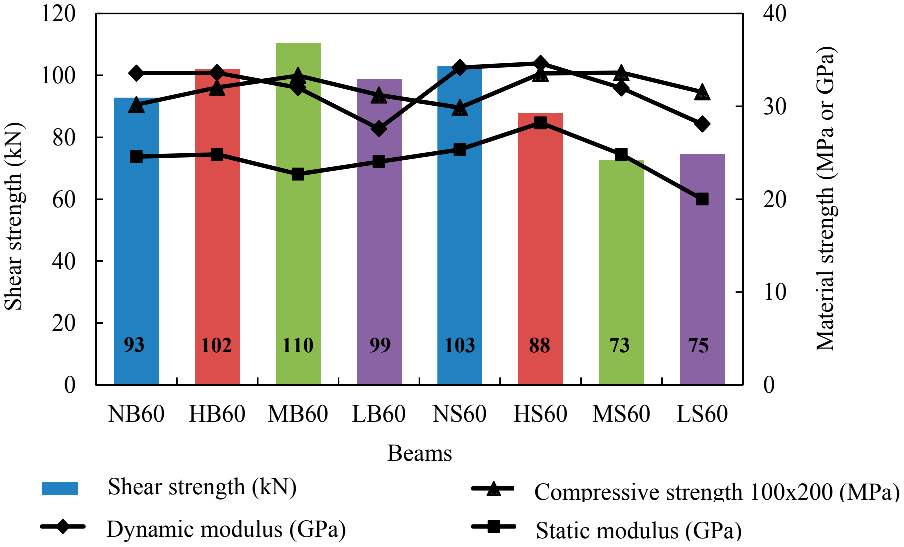


Figure 20. Shear strength of the RC beams and material properties of the concrete.

3.4.3. Size Effects on Shear Behavior

The shear strength of the RC beams increased with increases in the beam width and/or effective depth. However, the increase in the shear strength was not proportional to the increase in the beam size, even though the shear span-to-effective depth ratio was constant, as shown in Table 5, which presents the experimental data of the shear strength test of the RC beam, without shear reinforcement, using a natural aggregate (Taylor [23]). The beam size doubled by maintaining a shear span-to-effective depth ratio (*a/d*) of 3.0 and a reinforcement ratio (ρ) of 1.35%. Taylor reported that the average shear stress of the half-sized beams increased by a factor of 1.14 or 1.21, compared to that of the original beams. In contrast, the current experimental results indicated that the average shear stress of the small beams was 1.7 times higher than that of the large beams, regardless of the recycled aggregate quality. Dowel action contribution with the different ρ might have caused a difference of the shear strength between the small and large beams. The ultimate shear strength increased as the beam size increased. However, the shear stress calculated by Equation (2) was almost identical. In addition, the v_u of the small specimens was typically higher than that of the large specimens. In the JIS, the ultimate shear strength of the RC beam due to diagonal shear failure was calculated using Equation (3).

$$v_u = \frac{V_u}{b_w d} \tag{2}$$

$$V_u = 0.2 f_c'^{1/3} (100 p_w)^{1/3} \left(\frac{10^3}{d}\right)^{1/4} \left(0.75 + \frac{1.4d}{a}\right) b_w d \tag{3}$$

where v_u was the ultimate shear stress (MPa), V_u was the ultimate shear strength due to diagonal shear failure (N), f'_c was the compressive strength of concrete (MPa), $p_w = A_s/b_w d$ was the longitudinal tensile reinforcement ratio, d and b_w were the effective depth and width of the rectangular cross-section beam (mm), respectively, and a was the shear span (mm).

Table 5. Experimental results of the shear strength of the RC beam using natural aggregate concrete as given in Taylor [23].

No	**Section (mm)**			f'_c **(MPa)**	$V_{u,exp}$ **(kN)**	$V_{u,com}$ **(kN)**	$V_{u,exp}/V_{u,com}$	v_u	
	b	d	h					**(MPa)**	**Average**
A1	400	930	1000	29.2	358.4	313.71	1.14	0.84	0.82
A2				25.5	328.4	300.10	1.09	0.81	
B1	200	465	500	27.2	104.2	91.09	1.14	0.98	0.99
B2				24.9	87.3	88.44	0.99	0.95	
B3				32.1	85.3	96.26	0.89	1.04	
C1	100	232	250	25.6	22.5	26.50	0.85	1.14	1.13
C2				25.6	24.0	26.50	0.91	1.14	
C3				27.5	27.5	27.14	1.01	1.17	
C4				20.8	22.5	24.72	0.91	1.07	
C5				22.4	27.0	25.34	1.07	1.09	
C6				28.8	27.5	27.56	1.00	1.19	

Table 6 shows the experimental results of the shear strength of the RC beams, using a natural and recycled coarse aggregate concrete, without the shear reinforcement. The effective depth of the large beams was two times larger than that of the small beams. However, the large and small beams had the same cross-sectional area of reinforcement, resulting in half the reinforcement ratios for large beams, at 1.32%, versus 2.65% for the small beams. The shear strengths obtained experimentally were typically smaller than the estimated values, which ranged from 0.85 to 1.27.

Table 6. Experimental results of the shear strength of the RC beams using a natural and recycled aggregate concrete, without web reinforcement.

Notation	**Section (mm)**			a/d	ρ **(%)**	f'_c **(MPa)**	$V_{u,exp}$ **(kN)**	$V_{u,com}$ **(kN)**	$V_{u,exp}/V_{u,com}$	v_u	
	b	d	h							**(MPa)**	**Average**
NB60	150	300	325	2.5	1.32	30.17	46.39	54.45	0.85	1.03	1.12
HB60						32.03	51.05	55.55	0.92	1.13	
MB60						33.33	55.10	56.29	0.98	1.22	
LB60						31.21	49.45	55.07	0.90	1.10	
NS60		150	175		2.65	29.86	51.55	40.65	1.27	2.29	1.88
HS60						33.56	43.90	42.27	1.04	1.95	
MS60						33.62	36.30	42.29	0.86	1.61	
LS60						31.55	37.35	41.41	0.90	1.66	

For the large beams, the ultimate shear strength was consistent with the compressive strength of concrete, regardless of the effect of the recycled aggregate quality. However, the current estimation equation appeared to overestimate the shear strength of the large beam for all types of aggregate. Although the specimens had enough anchorage length and the local rebar slip at the anchorage region was not observed during the loading test, the splitting cracks as shown in Figure 16, might have affected the shear strength.

For the small beams, the ultimate shear strength of the natural aggregate increased from 46.39 to 51.55 kN, whereas the shear strength of all specimens made of recycled aggregate decreased to 43.90, 36.30, and 37.35 kN, for the high-, medium-, and low-quality recycled aggregate, respectively, irrespective of the compressive strength. The effects of the recycled aggregate quality could be clearly observed among the small beams. The aggregate interlocking mechanism had a greater influence on the shear strength of the smaller beam sizes. Similarly, the shear strength of the RC beams with different specimen sizes, shear span-to-effective depth ratios, and recycled aggregate types, found in the literature, are shown in Table 7. The recycled aggregate used in each experiment was classified, based on its density and water absorption, using the JIS.

Table 7. Shear strength of the RC beam using a recycled aggregate concrete, from the literature.

References	Section (mm)		a/d	ρ (%)	f'_c (MPa)	$V_{u,exp}$ (kN)	$V_{u,com}$ (kN)	$V_{u,exp}/V_{u,com}$	Class
	b	d							
Ji et al. [24]	170	270	2.0	1.10	31.6	66.65	60.79	1.09	N
	170	270	2.0	1.10	39.66	59.98	65.01	0.92	H
Kim et al. [12]	200	300	2.5	1.90	31.8	75.5	83.36	0.91	N
	200	450	2.5	1.90	31.8	106.9	112.92	0.95	N
	200	600	2.5	1.90	31.8	125.9	140.19	0.90	N
	300	450	2.5	1.90	31.8	156.7	171.41	0.91	N
	400	600	2.5	1.90	31.8	256.4	280.38	0.91	N
	200	300	2.5	1.90	34.9	72.9	85.98	0.85	H
	200	450	2.5	1.90	34.9	96.4	116.47	0.83	H
	200	600	2.5	1.90	34.9	125.1	144.61	0.87	H
	300	450	2.5	1.90	34.9	159.8	176.81	0.90	H
	400	600	2.5	1.90	34.9	256.6	289.21	0.89	H
Ikegawa et al. [25]	200	260	2.31	1.10	32.5	71.9	64.9	1.11	N
	200	260	2.31	1.10	34.8	57.15	66.40	0.86	L
	200	260	2.31	1.10	44.1	65.4	71.85	0.91	L
	200	260	2.31	1.10	42.4	81.4	70.92	1.15	L
Fathifazl et al. [11]	200	309	2.59	1.62	34.4	110.1	81.68	1.35	N
	200	300	1.50	1.00	43.5	195.7	95.99	2.04	M
	200	300	2.00	1.50	43.5	174.1	94.65	1.84	M
	200	305	3.93	2.46	43.5	106.3	86.22	1.23	M
	200	300	1.50	1.00	36.9	187.2	90.87	2.06	L
	200	300	2.00	1.50	36.9	165.6	89.60	1.85	L
	200	309	2.59	1.62	36.9	104.0	83.65	1.24	L
	200	305	3.93	2.46	36.9	83.8	81.62	1.03	L

3.5. Serviceability

Structural design, particularly for buildings, must consider the serviceability of the structures by satisfying the allowable deflection criteria, even though the ultimate limit state was generally verified in advance. The diversity of serviceability conditions could not all be handled by simply limiting the flexibility of the structures. Each individual condition must be addressed by the designer, for specific performance requirements.

For beams NB60, HB60, MB60, and LB60, the mid-span deflections corresponding to the ultimate load were 2.80, 5.37, 3.49, 7.08 mm, respectively. The corresponding mid-span deflection was not consistent with the shear strength. However, the shear strength of the RC beams made of recycled aggregate concrete was higher than that of the natural aggregate concrete beam, but the deflections of the high-, medium-, and low-quality recycled aggregate concrete beams were 1.92, 1.25, and 2.53 times higher, respectively. Therefore, careful consideration should be given when designing concrete structures using a low-quality recycled aggregate.

A better relationship between the shear strength and corresponding mid-span deflection could be achieved for the small beams. A higher shear strength was associated with a larger mid-span deflection. Beam MS60 had a 29.6% lower shear strength and a 54.9% lower deflection, than the beam NS60, indicating the improved performance of the medium-quality recycled aggregate, despite its lower shear strength. In contrast, beams HS60 and LS60 had 17.6% and 20.4% lower deflections and 14.8% and 27.5% lower shear strengths, respectively, than the beam NS60, which was nearly the same rate as that for the reduction in strength.

4. Discussions

Based on the results of the investigation of the effects of recycled aggregate quality on bond and shear behaviors of RC beams, using a recycled aggregate concrete, the following points can be discussed.

Concrete made with lower quality recycled aggregate always has a lower slump due to its higher water absorption capacity and excessive moisture loss from the aggregate, during a one-day drying period, before the concrete is mixed, resulting in a compressive strength comparable with natural concrete, without any attenuation in strength.

The bond strength of the concrete with the low-quality recycled coarse aggregate is always the lowest, but the bond strength deterioration could be ignored for the high- and medium-quality recycled aggregate concrete. In some cases, the bond strength of the concrete with the high- and medium-quality recycled coarse aggregate replacement is higher than that of the natural aggregate concrete. In addition, the bond between the concrete and different diameters of deformed rebar (13 and 19 mm) have highly similar bond behaviors and ultimate bond stresses, when the embedment length is maintained at the same ratio of four times the steel diameter.

Shear strength of recycled concrete beams decreases as the effective depth decreases. In contrast, the ultimate shear strength of natural concrete beams increases, even for smaller beam size. The estimated shear strength of all beams are larger than the experimental results, except for beam NS60 and HS60, having $V_{u,exp}/V_{u,com}$ of 1.27 and 1.04, respectively. The effect of high-quality of recycled aggregate on shear strength should not be considered. In this study, the shear strength of the large beams—HB60, MB60, and LB60—were found to be 10%, 17.5%, and 6.6% higher than the strength of beam NB60, respectively. This could be explained by a higher compressive strength of concrete with a recycled aggregate. However, the shear strength of small beams, HS60, MS60, and LS60 was 14.8%, 30.5%, and 27.5% lower than the strength of beam NS60, respectively. It could be concluded that the recycled aggregate qualities have a large effect on the shear behavior of small size RC beams, due to an aggregate interlock mechanism and this mechanism was negligible for large-size RC beams. However, further research is needed to investigate the effect of aggregate interlock for recycled concrete on the shear strength of the RC beam. In addition, Etxeberria et al. [26] found that the shear strength of RC beams with 25, 50, and 100% recycled coarse replacements was 3.7% higher, 15.4% lower, and 16.0% lower, respectively, than that of the RC beam made of natural aggregate concrete. Therefore, the recycled aggregate quality (medium- and low-quality) had an approximately two-fold larger effect than the 50% recycled aggregate replacement. In contrast, the effect of the high-quality recycled aggregate was almost equal to that of the 50% recycled aggregate replacement.

5. Conclusions

The following conclusions could be drawn based on the results of the current investigation, considering the effects of recycled aggregate quality on the material properties, bond behavior, and the shear strength of RC members, using a recycled aggregate concrete.

(1) Regarding the properties of fresh concrete with different recycled aggregate replacements and qualities, especially concrete with a recycled fine aggregate, the target workability could not be achieved easily, due to the various physical and mechanical properties of recycled aggregates. For instance, due to a higher fineness modulus of high- and medium-quality recycled fine aggregates, compared with the low-quality recycled fine aggregate, concrete requires approximately, a 3% greater mix of water, than concrete made by a low-quality recycled fine aggregate. As a result, a slump of fresh concrete made with a lower quality recycled fine aggregate has a lower slump, even though all coarse and fine aggregates are presoaked before the concrete mix. In contrast, concrete made with a lower quality recycled coarse aggregate has a comparatively higher slump. It might be due to the excessive water on the aggregate surface that could not be dried out completely by pieces of cloth. To overcome this, all coarse aggregates are dried out automatically one day before the concrete mix. As a result, the workability is almost the same, regardless of the effect of recycled aggregate qualities. However, all slump values are approximately 18 cm higher than the target value of 12 cm.

(2) The compressive strength of concrete with different recycled aggregate replacements and qualities is normally lower than the strength of natural concrete, followed by the flexural strength,

split tensile strength, static and dynamic elastic modulus, and the hardened concrete density. Even though the compressive strength of a high-quality recycled coarse aggregate concrete was 14% higher than that of natural concrete, only a little strength improvement could be observed for other material properties. In general, the strength of a high-quality recycled aggregate concrete is the highest followed by a medium- and low-quality recycled aggregate concrete. The dynamic elastic modulus is always lower for the lower quality recycled aggregate, irrespective of recycled aggregate replacements. Drying shrinkage of recycled concrete is generally higher than that of natural concrete.

(3) Bond strength of both natural and recycled concrete increased with a decrease in water to cement ratio but there was no strength development, when water to cement ratio decreased from 0.60 to 0.45. It could be explained by a sharp drop in density increment, which has a tendency to increase, and almost the same drying shrinkage and dynamic elastic modulus of the concrete for a water to cement ratio of 0.60 and 0.45, even though the compressive strength, split tensile strength, static elastic modulus, and the compressive strength of mortar increased smoothly with a decrease in water to cement ratio. High- and medium-quality recycled coarse aggregate have a very little effect on the bond strength of concrete and are sometimes higher. However, the bond strength of low-quality recycled coarse aggregate was always the lowest one. The variation among specimens for bond stress was very large, compared with the material properties test.

(4) Shear behavior of the RC beam with a natural and recycled concrete is very similar. The final beam failure due to shear occurs after the formation of a large diagonal crack. Just before, the maximum load, some beam specimens have several vertical cracks that form at the beam top or at the shear compression zone. The effects of recycled aggregate qualities could be revealed for the case of a small size beam. It might be due to a comparable effect of aggregate interlock mechanism and this effect is too small for the large-sized RC beams.

Further research is needed to conduct the numerical simulation for understanding the bond behavior and shear strength of RC specimens, with the recycled aggregates. It is also necessary to conduct an additional experiment for estimating the long-term structural performance of RC members, using the recycled aggregates.

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