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Impact of Concurrent Appointment of Quality and Environmental Managers on Post-Certification Quality Test Performance of Recycled Aggregates for Construction Applications

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Abstract

Maintaining consistent quality performance of recycled aggregates is essential for their reliable use in construction applications. This study evaluated whether the regulatory revision permitting concurrent appointment of quality and environmental managers affected post-certification quality test performance within Korea's recycled aggregate certification system. Extending a previous 2025 audit-based study, this research analyzed 311 certification-application-level follow-up quality test results obtained during the 2023 national post-certification management process. Statistical analyses, including chi-square tests, Fisher's exact tests, odds ratio comparisons, and subgroup analyses, were conducted according to management structure, personnel change status, and recycled aggregate application type. The results showed that concurrent appointment and personnel changes were not associated with statistically significant deterioration in post-certification quality test performance. In contrast, the recycled aggregate application type showed substantially greater influence on pass/fail outcomes, with relatively higher failure risks observed in concrete and fine aggregate applications requiring stricter quality control conditions. Road construction and asphalt concrete applications generally maintained relatively stable pass rates regardless of management structure or personnel continuity conditions. The subgroup analyses additionally showed that concurrent appointment did not significantly increase failure risk within any recycled aggregate application category. These findings indicate that concurrent appointment did not significantly deteriorate actual post-certification quality performance within the analyzed national certification dataset.

Keywords: recycled aggregates; quality performance; post-certification inspection; quality management; sustainable construction materials; construction waste recycling; recycled concrete aggregate; construction materials

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1. Introduction

The sustainable utilization of recycled construction materials has become increasingly important because of resource depletion and environmental concerns associated with the construction industry [1]. Among various recycled construction materials, recycled aggregates have received considerable attention as alternative construction materials applicable to road construction, concrete production, asphalt concrete, and other infrastructure applications [2]. Accordingly, many countries have introduced certification and

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quality management systems to secure the reliability and consistent quality performance of recycled aggregate products [3,4].

In Korea, certified recycled aggregate producers are managed under the Construction Waste Recycling Promotion Act and related certification regulations. In 2021, the relevant regulatory framework was revised to permit the concurrent appointment of quality and environmental managers within certified recycled aggregate production facilities [5]. The regulatory revision aimed to improve operational efficiency and reduce unnecessary management burdens while maintaining post-certification quality performance. Because recycled aggregate certification systems directly influence the reliability and sustainable utilization of recycled construction materials, verification of the regulatory revision through actual post-certification performance data is important [6].

The expanded use of recycled aggregates has received increasing attention because it can contribute to the development of a resource-circulating construction industry by promoting construction waste recycling and reducing the consumption of natural aggregates [7,8]. However, the quality of recycled aggregates is influenced by various factors, including source material characteristics, production processes, impurity content, gradation, density, and water absorption, resulting in substantial variability in the performance of recycled aggregate products [9,10].

Such quality variability has been recognized as a major challenge for ensuring the reliability and practical utilization of recycled aggregates as construction materials because their engineering performance may vary depending on aggregate characteristics and quality conditions [11,12]. Accordingly, recent studies have extensively investigated the physical properties, durability, optimal replacement ratios, and application-specific performance characteristics of recycled aggregates while also examining strategies for improving their sustainable utilization in construction applications [13,14].

In addition, maintaining consistent quality performance after certification requires effective quality-control practices throughout the production and management process. Within recycled aggregate certification systems, quality managers play a key role in quality testing, production-process control, compliance monitoring, and corrective actions for nonconforming products. Therefore, the effectiveness of post-certification quality management may be influenced not only by technical production factors but also by the management structure and operational conditions under which quality-control activities are performed. In particular, the regulatory relaxation permitting concurrent appointment of quality and environmental managers may raise concerns regarding increased workload, reduced managerial focus, and potential deterioration of quality-control effectiveness. Nevertheless, previous studies have primarily focused on the engineering properties, performance characteristics, and quality standards of recycled aggregates, whereas empirical evidence regarding the influence of quality-management structures on actual post-certification quality performance remains limited [15,16]. Therefore, further investigation is needed to determine whether concurrent appointment affects the quality stability of certified recycled aggregate products under actual operating conditions.

A previous study published in 2025 evaluated company-level post-certification audit outcomes associated with concurrent appointment and personnel continuity within Korea's recycled aggregate certification system using 2023 audit records [17]. The previous study statistically analyzed post-certification audit scores and reported that concurrent appointment and personnel changes were not associated with statistically significant deterioration in audit-based quality management performance. Accordingly, the regulatory relaxation permitting concurrent appointment was considered a reasonable institutional adjustment within the analyzed audit dataset.

However, the previous study primarily focused on company-level audit management outcomes rather than actual application-level quality test performance. Therefore, additional verification based on actual follow-up quality test results is necessary to determine whether the regulatory revision affected post-certification quality stability in certified recycled aggregate applications [18]. Furthermore, differences in recycled aggregate application type may influence pass/fail quality test outcomes because concrete and fine aggregate applications generally require stricter quality control conditions than road construction and asphalt concrete applications [19,20].

Therefore, this follow-up study evaluated actual post-certification quality test performance using 311 certification-application-level follow-up quality test records obtained during the 2023 post-certification management process in Korea's recycled aggregate certification system. Statistical analyses, including chi-square tests, Fisher's exact tests, odds ratio comparisons, and subgroup analyses, were conducted according to management structure, personnel change status, and recycled aggregate application type [21]. The objective of this study was to validate whether the regulatory relaxation permitting concurrent appointment significantly affected actual post-certification quality test performance within the analyzed national certification dataset.

2. Materials and Methods

2.1. Post-Certification Quality Test Dataset

This study analyzed post-certification follow-up quality test records obtained from certified recycled aggregate applications managed under Korea's recycled aggregate certification system [22]. The analyzed dataset consisted of 311 certification-application-level follow-up quality test cases collected during the 2023 post-certification management process [23]. The follow-up quality tests were conducted to verify whether certified recycled aggregate applications continuously satisfied the required quality standards after certification approval [24,25].

The analyzed recycled aggregate applications included road construction, concrete, fine aggregate, and asphalt concrete applications. Pass/fail outcomes identified during the follow-up quality testing process were used as the primary evaluation variable for statistical analysis. The collected records were anonymized before analysis, and only management structure, personnel continuity status, recycled aggregate application type, and follow-up quality test outcomes were used in this study. The overall research framework of the study, including the data selection process, variable classification scheme, and statistical analysis procedures, is presented in Figure 1.

2.2. Management Structure and Personnel Continuity Conditions

The analyzed certification applications were classified according to management structure and personnel continuity conditions. The management structure was classified as either dedicated management or concurrent appointment management. Concurrent appointment indicates that quality and environmental management responsibilities were simultaneously assigned to the same manager according to the revised regulatory framework [26]. Personnel continuity conditions were classified according to whether personnel changes occurred during the certification maintenance period. Accordingly, the analyzed certification applications were categorized into the following groups:

- Dedicated management without personnel changes;
- Concurrent appointment without personnel changes;
- Dedicated management with personnel changes;
- Concurrent appointment with personnel changes.

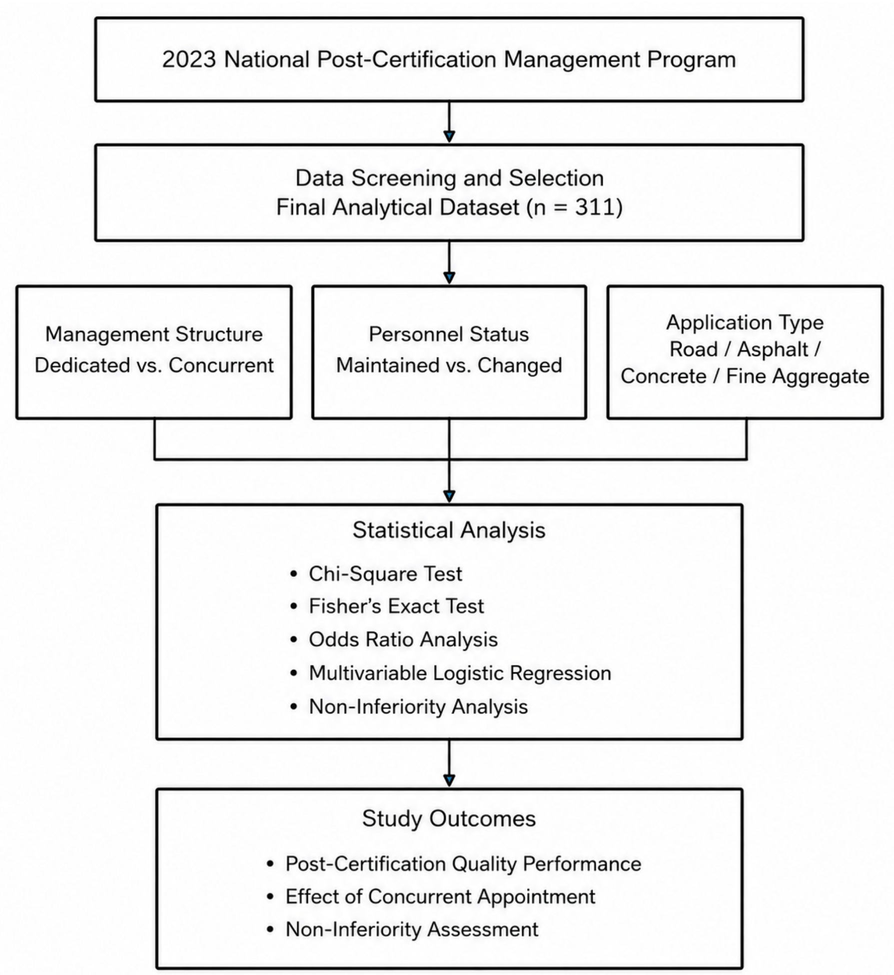

Figure 1. Research framework of the study.

The classification was used to statistically evaluate whether concurrent appointment and personnel changes affected actual post-certification quality test performance [27]. Personnel change status was recorded only as the occurrence or absence of personnel changes during the certification maintenance period. Detailed information regarding the nature, frequency, or duration of personnel changes, such as temporary replacement, permanent turnover, or multiple personnel changes, was not available in the analyzed dataset.

2.3. Statistical Analysis

Statistical analyses were conducted using pass/fail outcomes obtained from the post-certification follow-up quality tests. Chi-square tests and Fisher's exact tests were performed to evaluate statistical associations between management conditions and pass/fail outcomes. Odds ratio comparisons were additionally conducted to compare relative failure risks according to management structure and personnel continuity conditions.

Subgroup analyses were also performed according to recycled aggregate application type because different application categories may require different quality control conditions. Concrete and fine aggregate applications generally require stricter quality control conditions than road construction and asphalt concrete applications [28]. Therefore, application-type-based subgroup analyses were conducted to determine whether recycled aggregate application type exerted greater influence on post-certification quality test outcomes than management structure or personnel continuity conditions. All statistical analyses were conducted using a significance level of 0.05.

In addition, a multivariable logistic regression analysis was conducted to evaluate the independent effects of management structure, personnel change status, and recycled aggregate application type on post-certification quality test failure. Follow-up quality test failure was used as the dependent variable, and adjusted odds ratios (ORs), 95% confidence intervals (CIs), and *p*-values were calculated. Asphalt concrete applications were excluded from the regression model because no failure cases were observed in this category.

A non-inferiority analysis was additionally conducted to evaluate whether concurrent appointment was not unacceptably worse than dedicated management in terms of post-certification quality test failure. The risk difference in failure rates between concurrent appointment and dedicated management was calculated as concurrent appointment minus dedicated management. A non-inferiority margin of 10 percentage points was predefined. Non-inferiority was concluded when the upper bound of the 95% confidence interval for the risk difference was below the predefined non-inferiority margin.

3. Results

3.1. Overall Distribution of Post-Certification Quality Test Outcomes

A total of 311 certification-application-level follow-up quality test cases obtained during the 2023 post-certification management process were analyzed in this study. Among the analyzed cases, 256 applications passed the follow-up quality tests, whereas 55 applications failed, corresponding to an overall failure rate of 17.7%.

Table 1 presents the overall distribution of quality test outcomes according to management structure and personnel continuity conditions. Unexpectedly, concurrent appointment and personnel-change conditions showed slightly lower failure rates than dedicated-management and no-change conditions. However, subgroup composition and recycled aggregate application-type distributions were not identical among the analyzed conditions, indicating that additional statistical significance testing was necessary before interpreting these differences as independent management effects.

Table 1. Distribution of post-certification quality test outcomes according to management conditions.

Condition	Pass	Fail	Total	Fail Rate (%)
Dedicated management	151	38	189	20.1
Concurrent appointment	105	17	122	13.9
No personnel changes	198	45	243	18.5
Personnel changes	58	10	68	14.7
Total	256	55	311	17.7

3.2. Statistical Evaluation of Concurrent Appointment and Personnel Changes

To evaluate whether management structure and personnel continuity conditions significantly affected post-certification quality test outcomes, the null hypothesis that management conditions and pass/fail quality test outcomes were statistically independent was tested using chi-square and Fisher's exact tests. Table 2 summarizes the statistical evaluation results for concurrent appointment and personnel changes. Concurrent appointment did not show a statistically significant association with pass/fail quality test outcomes ($\chi^2 = 1.940$, $p = 0.164$). Fisher's exact test also showed no statistically significant association ($p = 0.174$). The odds ratio for failure risk under concurrent appointment was 0.643, and the 95% confidence interval included 1.0 (95% CI = 0.345–1.200).

Personnel changes also did not show a statistically significant association with pass/fail quality test outcomes ($\chi^2 = 0.531$, $p = 0.466$). Fisher's exact test similarly showed no statistically significant association ($p = 0.590$). The odds ratio for failure risk associated with personnel changes was 0.759, and the 95% confidence interval included 1.0 (95% CI = 0.360–1.598).

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These findings indicated that neither concurrent appointment nor personnel changes significantly increased failure risk within the analyzed national certification dataset.

Table 2. Statistical analysis results for concurrent appointment and personnel changes.

Comparison	χ^2	Chi-Square *p*-Value	Fisher's Exact *p*-Value	Odds Ratio	95% CI
Concurrent appointment vs. dedicated management	1.940	0.164	0.174	0.643	0.345–1.200
Personnel changes vs. no personnel changes	0.531	0.466	0.590	0.759	0.360–1.598

3.3. Combined Comparison of Management Conditions

To evaluate the combined influence of management structure and personnel continuity conditions, four management-condition subgroups were compared. Table 3 presents the pass/fail distributions according to the combined management conditions. The "concurrent appointment with personnel changes" condition unexpectedly showed the lowest failure rate (11.6%), whereas the "dedicated management without personnel changes" condition showed the highest failure rate (20.1%). However, the overall comparison among the four management conditions was not statistically significant (χ^2 = 2.183, df = 3, p = 0.535), indicating that simultaneous concurrent appointment and personnel changes did not significantly increase post-certification quality test failure risk.

Table 3. Pass/fail distributions according to combined management conditions.

Condition	Pass	Fail	Total	Fail Rate (%)
Dedicated management without personnel changes	131	33	164	20.1
Dedicated management with personnel changes	20	5	25	20.0
Concurrent appointment without personnel changes	67	12	79	15.2
Concurrent appointment with personnel changes	38	5	43	11.6
Total	256	55	311	17.7

To further evaluate relative failure risk differences among the management conditions, pairwise odds ratio comparisons were additionally conducted using the "dedicated management without personnel changes" condition as the reference condition. Table 4 shows that all confidence intervals included 1.0, indicating that none of the combined management conditions showed statistically significant increases in failure risk relative to the reference condition.

Table 4. Pairwise odds ratio comparisons among management conditions.

Comparison	Odds Ratio	95% CI	*p*-Value
Dedicated management with personnel changes vs. reference condition	0.992	0.347–2.841	0.989
Concurrent appointment without personnel changes vs. reference condition	0.711	0.345–1.466	0.354
Concurrent appointment with personnel changes vs. reference condition	0.522	0.191–1.431	0.200

These results further supported the interpretation that neither concurrent appointment nor personnel changes independently deteriorated actual post-certification quality test performance.

3.4. Statistical Differences According to Recycled Aggregate Application Type

To evaluate whether the recycled aggregate application type affected actual post-certification quality test outcomes, statistical comparisons among application categories were conducted. Table 5 presents the quality test outcomes according to recycled aggregate application type. The overall comparison among the four application types showed a highly statistically significant difference (χ^2 = 50.567, df = 3, $p < 0.001$), indicating that the recycled aggregate application type exerted substantially greater influence on quality test outcomes than management structure or personnel continuity conditions.

Table 5. Statistical comparison of recycled aggregate application types.

Application Type	Pass, Fail/Total	Fail Rate (%)	Odds Ratio	95% CI	*p*-Value
Road construction	178, 14/192	7.3	Reference	-	-
Concrete	60, 34/94	36.2	7.205	3.622–14.332	<0.001
Fine aggregate	6, 7/13	53.8	14.833	4.385–50.174	<0.001
Asphalt concrete	12, 0/12	0.0	-	-	-

Road construction applications showed the lowest failure rate (7.3%), whereas fine aggregate applications showed the highest failure rate (53.8%). Concrete applications also showed substantially higher failure rates than road construction applications. Because asphalt concrete applications showed zero failure cases, some inferential subgroup analyses excluded asphalt concrete applications to avoid unstable odds ratio estimation caused by zero-cell distributions [29].

As shown in Table 5, concrete applications showed significantly higher failure risk than road construction applications (OR = 7.205, $p < 0.001$), whereas fine aggregate applications showed the highest relative failure risk (OR = 14.833, $p < 0.001$). These results indicated that recycled aggregate application type represented the most influential explanatory factor affecting actual post-certification quality test outcomes [30].

To further investigate the relatively high failure rates observed in recycled concrete coarse aggregate and recycled fine aggregate applications, an additional analysis was conducted on the failed cases included in this study. As shown in Table 6, all failed road construction aggregate cases were associated with gradation requirements, whereas failures in recycled concrete coarse aggregate and recycled fine aggregate applications were associated not only with gradation requirements but also with oven-dry density and water absorption criteria. In addition, the number of quality test items differs according to the recycled aggregate application type. Road construction aggregates are evaluated using eight quality test items, whereas recycled fine aggregate and recycled concrete coarse aggregate applications are evaluated using ten and eleven quality test items, respectively. In particular, concrete-related recycled aggregates are required to satisfy not only gradation requirements but also aggregate quality characteristics such as oven-dry density and water absorption, resulting in more complex quality-control requirements than those applied to road construction aggregates. Furthermore, the Ministry of Land, Infrastructure and Transport (MOLIT) of Korea revised the recycled aggregate certification criteria in December 2021, relaxing the gradation requirements for road construction aggregates while strengthening the oven-dry density and water absorption requirements for recycled fine aggregates. These findings indicate that the quality-control requirements and quality criteria differ according to recycled aggregate application type and suggest that the higher failure rates observed in recycled concrete coarse aggregate and recycled fine aggregate applications are more closely related to application-specific quality requirements than to differences in management structure or personnel continuity conditions. Therefore, the application-type differences identified in this study may reflect differences in quality requirements associated with each application rather than the influence of management structure itself.

Table 6. Quality-control characteristics and major failure patterns according to recycled aggregate application type.

Application Type	Test Items (n)	Failure Rate (%)	Major Failure Characteristics Identified from Failed Cases
Road construction	8	7.3	All failed cases were associated with gradation requirements.
Concrete	11	36.2	Failures were primarily associated with gradation, oven-dry density, and water absorption requirements.
Fine aggregate	10	53.8	Failures were primarily associated with water absorption, oven-dry density, and gradation requirements.

3.5. Application-Type-Based Subgroup Analysis of Concurrent Appointment

Additional subgroup analyses were conducted to determine whether concurrent appointment significantly affected quality test outcomes within each recycled aggregate application category. Table 7 presents the subgroup analysis results according to recycled aggregate application type. Within all application-type subgroups, concurrent appointment did not significantly increase failure risk. All *p*-values exceeded 0.05, and all confidence intervals included 1.0.

Table 7. Results of the application-type-based subgroup analysis of concurrent appointment.

Application Type	Management Structure	Pass, Fail/Total	Fail Rate (%)	Odds Ratio	95% CI	*p*-Value
Road construction	Dedicated management	108, 9/117	7.7	Reference	-	-
	Concurrent appointment	70, 5/75	6.7	0.857	0.276–2.664	0.790
Concrete	Dedicated management	33, 23/56	41.1	Reference	-	-
	Concurrent appointment	27, 11/38	28.9	0.585	0.242–1.410	0.230
Fine aggregate	Dedicated management	3, 6/9	66.7	Reference	-	-
	Concurrent appointment	3, 1/4	25.0	0.167	0.012–2.368	0.164

In road construction applications, the failure rate under concurrent appointment (6.7%) was similar to that under dedicated management (7.7%) (OR = 0.857, p = 0.790). In concrete applications, concurrent appointment showed a lower failure rate (28.9%) than dedicated management (41.1%), although the difference was not statistically significant (OR = 0.585, p = 0.230). Fine aggregate applications showed the largest apparent subgroup difference, with failure rates of 66.7% under dedicated management and 25.0% under concurrent appointment. However, the difference was not statistically significant because of the limited sample size and wide confidence interval (OR = 0.167, 95% CI = 0.012–2.368, p = 0.164).

Overall, the subgroup analyses indicated that concurrent appointment did not significantly deteriorate actual post-certification quality test performance even within relatively strict quality-control categories such as concrete and fine aggregate applications.

3.6. Multivariable Logistic Regression Analysis

To further evaluate whether concurrent appointment independently affected post-certification quality test outcomes after controlling for potential confounding factors, a multivariable logistic regression analysis was conducted. Management structure, personnel change status, and recycled aggregate application type were included as independent variables, and follow-up quality test failure was used as the dependent variable. The results are summarized in Table 8.

Table 8. Multivariable logistic regression analysis of post-certification quality test failure.

Variable	Adjusted OR	95% CI	*p*-Value
Concurrent appointment vs. dedicated management	0.629	0.313–1.264	0.193
Personnel changes vs. no personnel changes	0.826	0.359–1.901	0.654
Concrete vs. road construction	7.366	3.686–14.722	<0.001
Fine aggregate vs. road construction	14.711	4.308–50.230	<0.001

Asphalt concrete applications were excluded from the regression model because no failure cases were observed in this category. The multivariable logistic regression analysis showed that concurrent appointment was not significantly associated with post-certification quality test failure after adjusting for personnel changes and recycled aggregate application type (adjusted OR = 0.629, 95% CI = 0.313–1.264, $p = 0.193$). Personnel changes were also not significantly associated with failure risk (adjusted OR = 0.826, 95% CI = 0.359–1.901, $p = 0.654$). In contrast, recycled aggregate application type remained a significant predictor of quality test outcomes. Compared with road construction applications, concrete applications (adjusted OR = 7.366, $p < 0.001$) and fine aggregate applications (adjusted OR = 14.711, $p < 0.001$) showed substantially higher failure risks. These results indicate that recycled aggregate application type exerted a substantially greater influence on post-certification quality performance than management structure or personnel continuity conditions.

Table 9 compares the unadjusted and adjusted effects of concurrent appointment and personnel changes on post-certification quality test failure. The adjusted odds ratios remained similar to the unadjusted estimates, and neither concurrent appointment nor personnel changes showed statistically significant associations with failure risk before or after adjustment. These findings indicate that the non-significant effects observed in the univariate analyses were not materially influenced by differences in recycled aggregate application type and further support the conclusion that concurrent appointment did not independently deteriorate post-certification quality performance.

Table 9. Comparison of unadjusted and adjusted effects.

Factor	Unadjusted OR	95% CI	*p*-Value	Adjusted OR	95% CI	*p*-Value
Concurrent appointment	0.643	0.345–1.200	0.174	0.629	0.313–1.264	0.193
Personnel changes	0.759	0.360–1.598	0.590	0.826	0.359–1.901	0.654

3.7. Non-Inferiority Analysis

To further evaluate whether concurrent appointment performed comparably to dedicated management, a non-inferiority analysis was conducted using the difference in post-certification quality test failure rates. The observed failure rate was 13.9% under concurrent appointment and 20.1% under dedicated management. The risk difference, calculated as concurrent appointment minus dedicated management, was −6.17 percentage points, with a 95% confidence interval of −14.56 to 2.22 percentage points. The upper bound of the 95% confidence interval was below the predefined non-inferiority margin of 10 percentage points. Therefore, concurrent appointment was demonstrated to be non-inferior to dedicated management with respect to post-certification quality test failure, as summarized in Table 10.

Table 10. Non-inferiority analysis of concurrent appointment compared with dedicated management.

Comparison	Failure Rate Difference (%)	95% CI	Non-Inferiority Margin (%)	Conclusion
Concurrent appointment—dedicated management	−6.17	−14.56 to 2.22	10.00	Non-inferior

4. Discussion

The present study statistically evaluated the effects of concurrent appointment and personnel changes on actual post-certification quality performance using 311 certification-application-level follow-up quality test cases obtained from the 2023 national post-certification management process for recycled aggregate certification in South Korea. The statistical results consistently showed that concurrent appointment did not significantly increase quality test failure risk. The failure rate under dedicated management was 20.1%, whereas the failure rate under concurrent appointment was 13.9%. However, both the chi-square test (p = 0.164) and Fisher's exact test (p = 0.174) showed no statistically significant differences. In addition, the odds ratio for concurrent appointment was 0.643, and the corresponding 95% confidence interval included 1.0.

Personnel changes also did not show statistically significant deterioration effects. The failure rate under personnel-change conditions was 14.7%, compared with 18.5% under no-change conditions. The chi-square test result was not statistically significant (p = 0.466), and the odds ratio was 0.759 with a 95% confidence interval including 1.0. The combined management-condition analysis showed similar tendencies. The "concurrent appointment with personnel changes" condition unexpectedly showed the lowest failure rate (11.6%). Nevertheless, the overall subgroup comparison was not statistically significant (p = 0.535), and all pairwise odds ratio comparisons showed confidence intervals including 1.0. These findings indicated that neither concurrent appointment nor personnel changes independently increased actual post-certification quality failure risk [31].

In contrast, the recycled aggregate application type showed highly significant statistical differences. The overall application-type comparison showed χ^2 = 50.567 and $p < 0.001$, indicating substantially stronger statistical influence than management structure or personnel continuity conditions. The multivariable logistic regression analysis produced consistent results after simultaneously adjusting for personnel changes and recycled aggregate application type. Similar multivariable analytical approaches have recently been applied to recycled aggregate studies to evaluate the independent effects of multiple influencing variables on performance outcomes [11]. Concurrent appointment was not significantly associated with post-certification quality test failure (adjusted OR = 0.629, p = 0.193), and personnel changes also remained non-significant (adjusted OR = 0.826, p = 0.654). In contrast, concrete and fine aggregate applications continued to show substantially higher failure risks than road construction applications. Previous studies have likewise demonstrated that recycled aggregate performance can be influenced by multiple interacting factors rather than a single management or material variable [13]. The non-inferiority analysis further demonstrated that concurrent appointment was not unacceptably worse than dedicated management in terms of post-certification quality test failure, because the upper bound of the 95% confidence interval for the failure-rate difference remained below the predefined non-inferiority margin. These findings further support the interpretation that recycled aggregate application type exerted a substantially greater influence on post-certification quality outcomes than management structure or personnel continuity conditions. Road construction applications showed the lowest failure rate (7.3%), whereas concrete and fine aggregate applications showed substantially higher failure rates of 36.2% and 53.8%, respectively [32,33]. Relative to road construction applications, the odds ratio was 7.205 for concrete applications and 14.833 for fine aggregate applications, and both comparisons were statistically significant at $p < 0.001$.

The application-type-based subgroup analyses produced similar conclusions. Concurrent appointment did not significantly increase failure risk within any application category. Even in relatively strict quality-control categories such as concrete and fine aggregate applications [34], all confidence intervals included 1.0, and all p-values exceeded 0.05. Although relatively large subgroup differences were observed in fine aggregate applications, the subgroup sample size was limited, and the confidence interval was extremely wide; therefore, the observed difference could not be interpreted as statistically reliable independent evidence [35].

The present findings are generally consistent with the previous 2025 Applied Sciences study, which analyzed audit-based management performance indicators within the Korean recycled aggregate certification system. The previous study reported that concurrent appointment and personnel changes did not significantly deteriorate post-certification management performance. The present study extended those findings by directly analyzing actual certification-application-level quality test outcomes rather than audit scores alone. Accordingly, the present study provides empirical evidence that concurrent appointment was not associated with significant deterioration in post-certification quality performance within the analyzed national dataset. However, because the present study was based on observational certification records, these findings should not be interpreted as definitive causal evidence that concurrent appointment itself had no effect on quality performance.

From a policy perspective, the present findings suggest that application-type-specific quality characteristics may exert substantially greater influence on quality outcomes than generalized restrictions on concurrent appointment or personnel continuity conditions [36]. Therefore, future quality-management strategies may require greater focus on relatively high-risk application categories, particularly concrete and fine aggregate applications.

As additionally shown in Table 6, the relatively high failure rates observed in concrete and fine aggregate applications were primarily associated with gradation, oven-dry density, and water absorption requirements. These findings suggest that future post-certification quality-management strategies may be more effective when focusing on application-specific quality-control challenges rather than on generalized restrictions regarding management structure. In particular, concrete and fine aggregate applications may benefit from more targeted follow-up inspections, enhanced monitoring of critical quality parameters, and timely corrective feedback when deficiencies are identified. Therefore, prioritizing quality-control resources for higher-risk application categories may provide a more effective approach for improving post-certification quality performance within recycled aggregate certification systems.

The present study was based on the 2023 national post-certification management dataset within the Korean recycled aggregate certification system; therefore, interpretation of the results should remain within the institutional and temporal scope of the analyzed dataset. In addition, some subgroup categories, particularly fine aggregate applications, involved relatively limited sample sizes, requiring cautious interpretation of subgroup analysis results.

Because the present study was based on observational certification records rather than a controlled experimental design, the findings should be interpreted with caution regarding causal relationships. Although the multivariable logistic regression analysis adjusted for management structure, personnel change status, and recycled aggregate application type, other potentially relevant factors, such as facility characteristics, production processes, raw material quality, and operational conditions, were not available in the certification records and therefore could not be included in the analysis. Previous studies have reported that observational studies may remain susceptible to residual confounding despite statistical adjustment [37]. In addition, recycled aggregate quality and performance can be influenced by various material characteristics, treatment methods, and production-related factors [9,15]. Consequently, the possibility of residual confounding and other sources of bias cannot be completely excluded, and the present findings should therefore be interpreted as evidence of statistical association rather than definitive causal evidence.

Furthermore, personnel change status was classified only according to whether personnel changes occurred during the certification maintenance period. Therefore, the present study could not evaluate potential differences associated with specific personnel-transition characteristics, such as temporary replacement, permanent turnover, or multiple personnel changes. Future studies incorporating more detailed personnel-transition information may provide additional insight into the relationship between personnel continuity and post-certification quality performance. Nevertheless, the present study remains meaningful because it quantitatively evaluated the effects of concurrent appointment and personnel changes using actual post-certification quality test outcomes and consistently demonstrated that recycled aggregate application type exerted substantially greater influence on quality outcomes.

5. Conclusions

The present study statistically evaluated the effects of concurrent appointment and personnel changes on actual post-certification quality performance using 311 certification-application-level follow-up quality test cases obtained from the 2023 national post-certification management process for recycled aggregate certification in South Korea. As a follow-up study to the previous audit-based study published in *Applied Sciences* in 2025, the present study extended the previous findings to the level of actual quality test outcomes after certification. The statistical results showed that neither concurrent appointment nor personnel changes significantly increased post-certification quality failure risk. Chi-square tests, Fisher's exact tests, odds ratio analyses, and confidence interval analyses consistently failed to support the interpretation that concurrent appointment or personnel changes represented independent quality-deterioration factors. The combined management-condition analysis also showed that actual quality failure risk did not significantly increase even when concurrent appointment and personnel changes simultaneously existed.

In contrast, the recycled aggregate application type showed a highly significant statistical association with actual quality test outcomes. The overall application-type comparison showed $\chi^2 = 50.567$ and $p < 0.001$, while concrete and fine aggregate applications showed substantially higher failure risks than road construction applications. Furthermore, the application-type-based subgroup analyses consistently showed that concurrent appointment did not produce statistically significant deterioration effects within any application category. These findings indicated that recycled aggregate application type exerted substantially greater influence on actual post-certification quality outcomes than management structure or personnel continuity conditions. Furthermore, the multivariable logistic regression analysis consistently showed that concurrent appointment was not significantly associated with post-certification quality test failure after adjusting for personnel changes and recycled aggregate application type. In addition, the non-inferiority analysis demonstrated that concurrent appointment was non-inferior to dedicated management with respect to post-certification quality test failure under the predefined 10-percentage-point non-inferiority margin. These findings further support the conclusion that concurrent appointment did not independently deteriorate post-certification quality performance within the analyzed national certification dataset. The present findings were generally consistent with those of the previous audit-based study and further demonstrated that statistically significant quality deterioration associated with concurrent appointment was not identified even at the level of actual certification-application-level quality test outcomes. Accordingly, the present study provides additional empirical evidence that concurrent appointment was not associated with significant deterioration in post-certification quality performance within the analyzed national post-certification dataset.

Although incorporating multiple years of post-certification quality test data could increase the sample size and provide additional evidence regarding long-term performance trends, the present study was intentionally designed as a follow-up investigation to the previous audit-based study conducted using the same 2023 post-certification management dataset [17]. Using the identical observation-year dataset allowed for direct comparison between audit-based management outcomes and actual quality test outcomes, thereby ensuring methodological continuity and improving the interpretability of the combined findings. Nevertheless, future studies incorporating multiple years of post-certification quality test data would be valuable for further validating the long-term stability and generalizability of the present conclusions under varying operational and regulatory conditions.

The findings additionally suggest that future quality-management strategies for recycled aggregate certification may require greater focus on relatively high-risk application categories, particularly concrete and fine aggregate applications, rather than generalized reinforcement of concurrent appointment or personnel-management restrictions. Overall, the present study is meaningful in that it quantitatively demonstrated, using actual national post-certification quality test data, that recycled aggregate application type exerted substantially greater influence on quality outcomes than concurrent appointment or personnel continuity conditions.

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