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A Comparative Study on Mortar Removal Methods and their Influence on Recycled Aggregate Properties

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Abstract

The adhered mortar attached to recycled aggregate (RA) is one of the main causes of weakening the mechanical properties and durability performance of recycled aggregate concrete (RAC). Therefore, in order to improve the performance of RA and RAC, several methods have been proposed to remove the adhered mortar in RA. However, knowing the adhered mortar content is as important as removing it. This is because concrete mix designs considering the amount of adhered mortar have been proposed and better strength, durability and environmental benefits of these mix designs were reported compared to conventional RAC mix design. Therefore, in this study, the adhered mortar was removed by using two methods of 'acid treatment' and 'chemical and mechanical stress treatment' for three types of RA, and the test results obtained from each method were comparatively analyzed. The results showed that the adhered mortar contents determined by the two methods were different for the same aggregate, and neither allowed the complete removal of the adhered mortar from RA. It also showed that the test environment of the chemical-mechanical stress method can be harsh enough to damage the original aggregate in RA, and that the acid treatment can cause corrosion of RA depending on the type of aggregate.

Keywords

mortar removal, adhered mortar, recycled aggregate, mortar removal treatment

1 Introduction

Construction waste generation has increased in several countries due to urbanization, industrialization, economic growth and urban reconstruction. In 2018, approximately 600 million tons of construction waste were generated in the United States [1]. China produced approximately 1.59 billion tons of construction waste in 2017: only 10% of that waste was recycled and the rest was disposed of through illegal dumping or landfilling [2]. In general, concrete waste makes up the largest proportion of construction waste [3, 4]. Moreover, as about 60–75% of concrete consists of aggregates. Producing and reusing recycled aggregate (RA) from concrete waste offers a more environmentally sustainable alternative to the natural aggregate mined for the production of concrete while treating a large amount of construction waste. Therefore, using RA to produce concrete with similar performance to natural aggregate concrete is crucial for the sustainable development of the construction industry.

Many studies have developed methods for mixing RA into concrete, and have studied the physical and mechanical properties and durability of recycled aggregate concrete (RAC) [5, 6]. In general, it has been reported that RA can negatively affect various properties of concrete [7, 8]. Tüfekçi and Çakır [9] reported that significant slump loss was observed after 15 minutes of testing due to the high water absorption of RA, despite the use of superplasticizer in concrete and pre-wetting of the RA. In addition, poor performance in RAC is clearly observed as the replacement ratio of the RA increases [10, 11]. It is considered that the adhered mortar attached to RA contributes to this deterioration of RAC properties [12]. The effect of adhered mortar of RA on the properties of RAC was evaluated by several researchers. Kim et al. [13] produced two RAs with different physical characteristics by crushing concrete waste from the same source with different crushers. According to the study, the 28-day compressive

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strength of RAC made with RA with the adhered mortar content of 12% decreased by 9.1%, while the strength of RAC was further decreased by 15% when using RA with the adhered mortar content of 50%. Similarly, Duan and Poon [14] investigated the properties of RAC using three RAs with different adhered mortar contents of 19%, 36% and 62%, respectively. When the adhered mortar content was increased from 19% to 36% and 62%, the compressive strength of RAC decreased by 17% and 21%, and the drying shrinkage deformation increased by 33% and 48%. As a result of these findings, various methods for removing the adhered mortar from the RA have been proposed to improve the quality of RA. Abbas et al. [15] observed mortar degradation in RA by immersing RA in magnesium sulfate ($MgSO_4$), magnesium chloride ($MgCl_2$), and sodium sulfate (Na_2SO_4) solutions. Significant degradation of the adhered mortar was observed in RA immersed in Na_2SO_4 solution, whereas no significant mortar degradation was observed in RAs soaked in $MgSO_4$ and $MgCl_2$ solutions. For faster and more efficient mortar removal, the chemical decomposition method was combined with the mechanical stress method. RA samples were soaked in each solution for 6 hours, frozen at -18 °C for 12 hours, then thawed at room temperature. This process was repeated five times. After the test, the authors proposed a further modified method, and the reliability of the adhered mortar content calculated by this method was verified through image analysis. The modified method procedure is described in the following section.

Tam et al. [16] proposed a method to remove the adhered mortar by immersing RA in hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and phosphoric acid (H_3PO_4) solutions, respectively. Kim et al. [17] reported that the compressive strength of concrete containing RA subjected to the HCl treatment was 14% higher than that of concrete with untreated RA. Although some acid treatments leave traces of Cl- and SO4- ions in the treated RA, which can harm the durability of RAC, Ismail and Ramli [18] noted that the use of low-concentration acid solutions does not appear to be detrimental to RA. In that study, the authors immersed RA in three HCl solutions with different molar concentrations of 0.1, 0.5, and 0.8M for 1, 3, and 7 days. The authors observed an increase in adhered mortar loss as the molarity of the solution increased, but concluded that the soaking time did not significantly affect the amount of mortar loss.

Novel mix design methods for RAC considering the amount of adhered mortar have been proposed and their outstanding performance has been proven, underscoring the importance of measuring the adhered mortar content [19–23]. Moreover, in order to more accurately evaluate the effect of adhered mortar on cement composites, an accurate estimation of the adhered mortar content should be preceded. Due to this importance, several methods for measuring adhered mortar content have been proposed by several researchers, but an extensive comparative analysis of the proposed methods for the same RA has not been conducted. Therefore, this study compares commonly used methods aimed at determining the adhered mortar content using HCl and Na_2SO_4 solutions. Specific gravity, water absorption, and quality of RA based on Japanese Industrial Standards (JIS) A5021 [24] and A5023 [25] were evaluated before and after each method.

2 Materials and methods

2.1 Aggregates

Natural crushed aggregate (CA) obtained from a quarry and three RAs (i.e., RA1, RA2 and RA3) produced from concrete waste were used. The RA1 and RA2 were collected from the same source of road pavement concrete waste, but they were produced differently: RA1 was crushed a total of 5 times so that the aggregate had an overall round grain shape, while RA2 was crushed fewer times, producing a rough aggregate shape. RA3 was obtained from an airport runway concrete waste through secondary crushing with a jaw crusher and a cone crusher. There were no visible impurities (e.g., brick, ceramic and asphalt) in the RAs. The nominal maximum aggregate size was 25 mm.

2.2 Chemical-mechanical stress method

The chemical-mechanical stress method, one of the methods for determining the adhered mortar content, was proposed by Abbas et al. [15], which combines the aggregate soundness test and concrete scaling test. The test procedure is as follows. RAs that can represent each group are sampled by size. The suggested sample weight is 1000 g for 4.75–9.5 mm fractions and 2000 g for larger size fractions. The samples are dried in an oven at 105 °C for 24 hours (M1) and then immersed in 26% (by weight) Na_2SO_4 solution for 24 hours. The samples immersed in the solution are frozen at -17 °C for 16 hours then thawed at 80 °C for 8 hours. Freeze-thaw is repeated for a total of 5 cycles. After the end of the last cycle, the solution is drained and the samples are washed with tap water. Aggregates with sizes smaller than 4.75 mm are removed by sieving. The adhered mortar remaining on the aggregate surface even after the treatment is manually removed. The aggregate samples are then

dried in an oven at 105 °C for 24 hours and weighed (M2). The adhered mortar content is determined by comparing the weight loss before and after the treatment (Eq. 1). Fig. 1 shows the RA before and after the treatment. The test is performed twice for all RAs, and the adhered mortar content is presented by the size of the aggregate.

$$Adhered\ mortar\ content, \% = \left[\frac{M1 - M2}{M1}\right] \times 100 \quad (1)$$

2.3 Acid treatment

A method of removing adhered mortar using HCl solution was proposed by Tam et al. [16]. Compared to other methods of removing the adhered mortar, the acid treatment has a shorter test period of 24 hours and does not require an additional operation after soaking RA in the acid solution. In this study, HCl with a concentration of 1M is used to efficiently remove the adhered mortar. The test procedure is as follows. Representative samples of RA are obtained and weighed after drying in an oven at 105 °C for 24 hours (M1), then soaked in 1M HCl solution for 24 hours. To ensure an effective degradation reaction between the acid solution and the mortar, the container was shaken occasionally. At the end of the test, the acid solution is poured out and the sample is washed with tap water. Aggregates smaller than 4.75 mm are filtered out through sieving and the remaining samples are dried in an oven at 105 °C for 24 hours (M2) (Fig. 2). Equation 1 is used to determine the adhered mortar content. The test is performed for each size fraction and for all size fractions (4.75–25 mm), respectively.

Fig. 1 Recycled aggregate before and after chemical-mechanical stress treatment

3 Results and discussions

Table 1 shows the initial and final oven-dried weight and the weight loss by the size of RA samples that were subjected to freeze-thaw action for 5 cycles after immersion in Na2SO4 solution. Table 2 presents the test results of soaking the aggregates in a 1M HCl solution for 24 hours. As in the other literature, this weight loss is used as the adhered mortar content [15, 16, 20].

The test results of RA1, the high-quality RA with water absorption of 2.87% and oven-dry specific gravity of 2.50, were similar in both the chemical-mechanical stress method and the acid treatment. The weight loss of the RA1 sample following the chemical-mechanical stress method was 11.3–11.9%. The weight loss of RA1 after acid treatment was in the range of 11.2–11.3%. However, the low-quality RA, RA2, from the same source showed different results in the same test. When the chemical-mechanical stress method was performed twice, the first test showed that the adhered mortar content of RA2 was 51.8%, and the second test showed 37.0%. Also, in acid treatment, a weight loss of 36.6% after the first treatment and 29.5% after the second

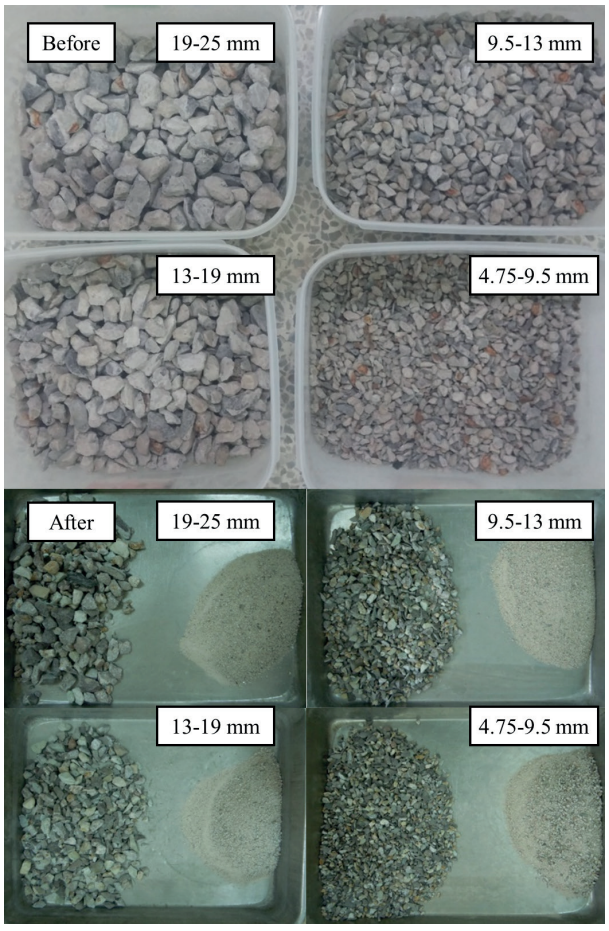

Fig. 2 Recycled aggregate before and after acid treatment

Table 1 Weight change by chemical mechanical stress method

ID	Initial oven-dried weight, g				Final oven-dried weight, g				Loss of weight, %				
	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	Avr. (4.75–25 mm)
CA	1001	749	500	300	975	733	493	298	2.6	2.1	1.3	0.8	2.0
RA1 #1	2100	2000	2146	1000	1904	1800	1860	860	9.3	10.0	13.3	14.0	11.3
RA1 #2	2002	1880	2004	902	1756	1733	1724	768	12.3	7.8	14.0	14.9	11.9
RA2 #1	2025	2000	1950	1000	635	860	1248	620	68.6	57.0	36.0	38.0	51.8
RA2 #2	1950	1842	2004	1084	835	1362	1616	519	57.2	26.1	19.4	52.1	37.0
RA3 #1	3999	1231	1165	1190	3130	890	790	800	21.7	27.7	32.2	32.8	26.0
RA3 #2	1491	1005	749	500	892	597	455	326	34.9	39.3	40.6	40.5	39.0

Table 2 Weight change by acid treatment

ID	Initial oven-dried weight, g				Final oven-dried weight, g				Loss of weight, %				
	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	19–25 mm	13–19 mm	9.5–13 mm	4.75–9.5 mm	Avr. (4.75–25 mm)
CA	4145				4132				0.3				0.3
RA1 #1	2088	2000	1986	1417	1810	1800	1777	1254	13.3	10.0	10.5	11.5	11.3
RA1 #2	1998				1774				11.2				11.2
RA2 #1	2290	1911	2063	1011	1494	1224	1245	649	34.8	35.9	39.7	35.8	36.6
RA2 #2	1875				1321				29.5				29.5
RA3 #1	2300	2301	2302	1150	1560	1410	1360	565	32.2	38.7	40.9	50.9	39.2
RA3 #2	2298				1490				35.2				35.2

treatment was observed. This means that there is a difference of 14.8% in weight loss in the chemical mechanical stress method and 7.1% in the acid treatment. A similar trend was observed for RA3, another low-quality RA with water absorption of 5.28% and an oven-dry specific gravity of 2.41. The difference in weight loss between the first test and the second test of chemical mechanical treatment was 13%, and the weight loss difference after acid treatment was 4%. These differences may be attributable to the production of RA or RA sampling process for testing.

In general, the RA production consists of crushing concrete waste, removing foreign substances, and screening by size. Masses of similar size fall into the category of RA, regardless of cement paste, cement mortar, or aggregate. In the study performed by Kim [26], the author classified RA into 'mortar-covered aggregates', 'clean aggregates' and 'partially liberated aggregates'. Thus, when sampling RAs of the same size, some aggregates may have less adhered mortar, while others may have only mortar masses with no aggregate. The upper row of Fig. 3 shows the appearance of RA1 and RA2 before the mortar removal treatment. In RA1, the adhered mortar is 'attached' to the original aggregate, whereas in RA2, the adhered mortar 'covers' the original aggregate, making it particularly difficult to visually distinguish whether each individual

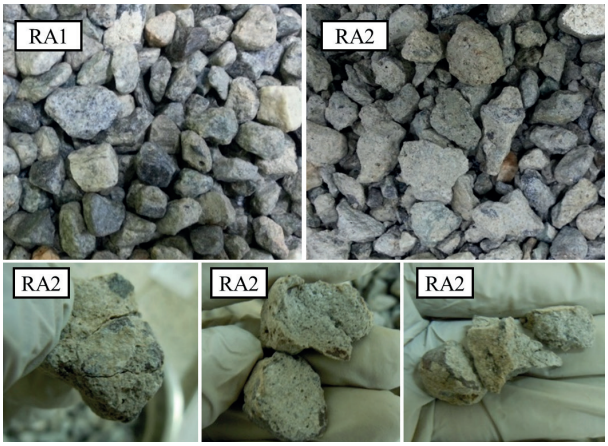

Fig. 3 Various recycled aggregates used in the study

RA2 mass is actually a mixture of original aggregate and adhered mortar or just mortar mass. For this reason, if a low-quality RA is used for the test, the deviation of the test results may increase. It may also be related to the quality of the RA produced. The RA1, RA2, and RA3 were subjected to mechanical crushing, 5 times for RA1 and twice for RA2 and RA3. Thus, RA1 may be less vulnerable to physical and chemical stress as compared to RA2 and RA3 because parts that are susceptible to impact and abrasion may have already been removed from the aggregate during the mechanical crushing process.

Regarding the relationship between the RA size and the adhered mortar content, contradictory research results were obtained. In the chemical-mechanical stress method, RA1 and RA3 were determined to have a higher adhered mortar content in smaller aggregates (i.e., 4.75–9.5 mm). RA2 had the highest adhered mortar content at an aggregate size of 19–25 mm. In the acid treatment, the adhered mortar content of RA3 followed the trend of the chemical mechanical treatment. That is, the adhered mortar content was high in the small-sized aggregate, but RA1 had the highest adhered mortar content at an aggregate size of 19–25 mm. These contradictory results are also observed in the literature. Bai et al. [27] observed that cement mortar accumulates in small-sized RA as concrete waste is gradually broken during the crushing process, and Suryawanshi et al. [28] found that the adhered mortar of 4.75–10 mm aggregate was about double that of 10–20 mm aggregate. On the other hand, more adhered mortar is observed in larger-sized aggregate [29, 30]. Also, no particular relationship between aggregate size and adhered mortar content was observed in the following studies [14, 15], implying that the crushing process of concrete waste affects the characteristics of RA.

With regards to the removal efficiency of adhered mortar, neither method achieved complete removal of adhered mortar from RA, consistent with previous research [31–33]. As can be seen at the bottom of Fig. 3, the interface between the original aggregate and the adhered mortar was weakly coupled after the treatment, allowing easy separation of the aggregate from the adhered mortar. Nevertheless, there was still residual adhered mortar that had not been removed.

Fig. 4 and Fig. 5 show the oven-dry specific gravity and water absorption before and after each treatment along with RA quality according to JIS requirements [24, 25]. RA with an oven-dry specific gravity greater than 2.5 is classified as high quality, greater than 2.3 as medium quality, and less than 2.3 as low quality. For the water absorption, less than 3% is classified as high-quality RA, less than 5% as medium-quality, and less than 7% as low-quality. RA1, RA2, and RA3 used in the study are classified as high-, low- and low quality, respectively. After applying both methods, all RAs met the requirements for high-quality, except for RA3 after the chemical-mechanical stress method.

The adhered mortar content of RA is generally proportional to the water absorption. Thus, the mortar removal efficiency can be evaluated by comparing the water absorption of untreated RA and treated RA. As expected, the specific gravity and water absorption of CA did not change before and after the treatments, and the RAs showed an increase in specific gravity and a decrease in water absorption.

The water absorption of RA1, RA2 and RA3 subjected to the acid treatment were 0.24%, 0.21%, and 0.35% lower than those of RAs subjected to the chemical-mechanical stress method. Regarding specific gravity, the RAs that had undergone acid treatment had 0.2–0.3 higher specific gravity, showing higher efficiency of mortar removal. Although the weight loss (i.e., adhered mortar content) of RA2 with the chemical-mechanical stress method is up to 15.2% higher than that of RA2 with the acid treatment, this does not mean that the former treatment can be considered more efficient in removing the adhered mortar. This is because higher water absorption and lower specific gravity were observed in RA2 after the acid treatment. This may be because the high and low-temperature environment combined with Na2SO4 solution is too harsh for certain aggregates. The natural aggregate used in this study had a weight loss of 2% in the chemical-mechanical

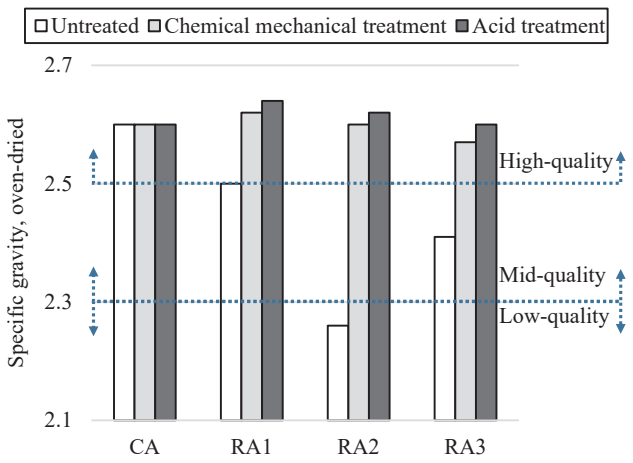

Fig. 4 Oven-dried specific gravity of aggregates used before and after treatments

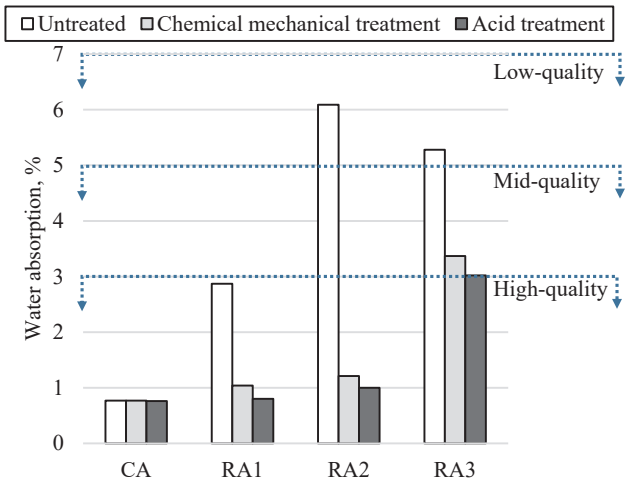

Fig. 5 Water absorption of aggregates used before and after treatments

Fig. 6 Natural aggregate damaged by hydrochloric acid

treatment method. If this method only removes adhered mortar, it should theoretically be 0%. Braymand et al. [34] noted that damage was observed in original aggregates of RA after freeze-thaw test at -17.5 °C. Therefore, the chemical mechanical stress method with Na_2SO_4 solution may overestimate the adhered mortar content.

In addition, in the visual inspection conducted after the test, damage to the aggregate by HCl was observed in the granite natural aggregate (Fig. 6). In particular, when estimating the adhered mortar content of RA containing limestone, the acid treatment should be avoided [35]. Therefore, the effectiveness of both treatment methods with respect to adhered mortar removal cannot be evaluated on the basis of weight loss.

4 Conclusions

In this study, two methods for removing adhered mortar from recycled aggregate were compared and analyzed, and the following conclusions can be drawn.

1. Both acid treatment and chemical-mechanical stress methods were effective in removing adhered mortar from RA. With the exception of RA3 after the chemical-mechanical stress method, all RAs used in the study met the requirements for high-quality RA.
2. RAs treated with acid showed 0.2-0.3 higher specific gravity and 0.21-0.35% lower water absorption than those treated with the chemical-mechanical stress method, indicating better mortar removal efficiency.
3. For the high-quality RA (RA1), the results of the chemical-mechanical stress method and the acid treatment for determining the adhered mortar content were similar. However, the test results for the low-quality RAs (RA2 and RA3) showed a difference in adhered mortar content according to the two treatment methods. This varies depending on whether the component that dominates one RA is mortar or the original aggregate.
4. Neither test allowed complete removal of the adhered mortar of the RAs used in the study. However, it is possible to manually remove the mortar by impacting the interface between the original aggregate and the mortar, after it has been weakened by the treatment process, allowing for the approximate content of the adhered mortar to be determined.
5. The chemical-mechanical stress method can provide too harsh environment for the original aggregate, causing weight loss greater than the actual adhered mortar content. The acid treatment can also cause damage in certain aggregates. Therefore, regardless of the method, an analysis of the aggregate needs to be done in advance.

The findings of this study are limited to the RAs used in this study. Therefore, further studies should be conducted to accurately estimate the adhered mortar content for specific RAs; e.g., different types of aggregates (i.e., rock types, different water absorption, properties of the parent concrete).

References

[1] EPA "Advancing Sustainable Materials Management: 2018 Fact Sheet Assessing Trends in Material Generation and Management in the United States", United States Environmental Protection Agency Research Triangle Park, Durham, NC, USA, 2020.

[2] Liu, J., Nie, J., Yuan, H. "Interactive decisions of the waste producer and the recycler in construction waste recycling", Journal of Cleaner Production, 256, Article number: 120403, 2020. https://doi.org/10.1016/j.jclepro.2020.120403

[3] Begum, R. A., Siwar, C., Pereira, J. J., Jaafar, A. H. "A benefit-cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia", Resources, Conservation and Recycling, 48(1), pp. 86–98, 2006. https://doi.org/10.1016/j.resconrec.2006.01.004

[4] Kim, J. "Construction and demolition waste management in Korea: recycled aggregate and its application", Clean Technologies and Environmental Policy, 23, pp. 2223–2234, 2021. https://doi.org/10.1007/s10098-021-02177-x

[5] Tam, V. W. Y., Tam, C. M. "Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc", Construction and Building Materials, 22(10), pp. 2068–2077, 2008. https://doi.org/10.1016/j.conbuildmat.2007.07.024

[6] Sičáková, A., Urbán, K., Kováč, M. "Slump Loss of Concrete Based on RCA and Prepared by Specific Mixing Approach", Periodica Polytechnica Civil Engineering, 62(4), pp. 1015–1020, 2018. https://doi.org/10.3311/PPci.11733

[7] Grabiec, A. M., Kim, J., Ubysz, A., Bilbao, P. "Some Remarks towards a Better Understanding of the Use of Concrete Recycled Aggregate: A Review", Sustainability, 13(23), Article number: 13336, 2021.
https://doi.org/10.3390/su132313336

[8] Kapoor, K., Singh, S. P., Singh, B. "Improving the Durability Properties of Self-Consolidating Concrete made with Recycled Concrete Aggregates using Blended Cements", International Journal of Civil Engineering, 19(7), pp. 759–775, 2021.
https://doi.org/10.1007/s40999-020-00584-7

[9] Tüfekçi, M. M., Çakır, Ö. "An Investigation on Mechanical and Physical Properties of Recycled Coarse Aggregate (RCA) Concrete with GGBFS", International Journal of Civil Engineering, 15(4), pp. 549–563, 2017.
https://doi.org/10.1007/s40999-017-0167-x

[10] Ceia, F., Raposo, J., Guerra, M., Júlio, E., De Brito, J. "Shear strength of recycled aggregate concrete to natural aggregate concrete interfaces", Construction and Building Materials, 109, pp. 139–145, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.02.002

[11] Domingo, A., Lázaro, C., Gayarre, F. L., Serrano, M. A., López-Colina, C. "Long term deformations by creep and shrinkage in recycled aggregate concrete", Materials and Structures, 43(8), pp. 1147–1160, 2010.
https://doi.org/10.1617/s11527-009-9573-0

[12] Fan, Y., Xiao, J., Tam, V. W. Y. "Effect of old attached mortar on the creep of recycled aggregate concrete", Structural Concrete, 15(2), pp. 169–178, 2014.
https://doi.org/10.1002/suco.201300055

[13] Kim, N., Kim, J., Yang, S. "Mechanical strength properties of RCA concrete made by a modified EMV method", Sustainability, 8(9), Article number: 924, 2016.
https://doi.org/10.3390/su8090924

[14] Duan, Z. H., Poon, C. S. "Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars", Materials and Design, 58, pp. 19–29, 2014.
https://doi.org/10.1016/j.matdes.2014.01.044

[15] Abbas, A., Fathifazl, G., Burkan Isgor, O., Razaqpur, A. G., Fournier, B., Foo, S. "Proposed method for determining the residual mortar content of recycled concrete aggregates", Journal of ASTM International, 5(1), pp. 1–12, 2008.
https://doi.org/10.1520/JAI101087

[16] Tam, V. W. Y., Tam, C. M., Le, K. N. "Removal of cement mortar remains from recycled aggregate using pre-soaking approaches", Resources, Conservation and Recycling, 50(1), pp. 82–101, 2007.
https://doi.org/10.1016/j.resconrec.2006.05.012

[17] Kim, Y., Hanif, A., Kazmi, S. M. S., Munir, M. J., Park, C. "Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates – Comparative assessment of assorted techniques", Journal of Cleaner Production, 191, pp. 339–349, 2018.
https://doi.org/10.1016/j.jclepro.2018.04.192

[18] Ismail, S., Ramli, M. "Engineering properties of treated recycled concrete aggregate (RCA) for structural applications", Construction and Building Materials, 44, pp. 464–476, 2013.
https://doi.org/10.1016/j.conbuildmat.2013.03.014

[19] Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., Foo, S. "New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate", Journal of Materials in Civil Engineering, 21(10), pp. 601–611, 2009.
https://doi.org/10.1061/(ASCE)0899-1561(2009)21:10(601)

[20] Jang, H., Kim, J., Sicakova, A. "Effect of Aggregate Size on Recycled Aggregate Concrete under Equivalent Mortar Volume Mix Design", Applied Sciences, 11(23), Article number: 11274, 2021.
https://doi.org/10.3390/app112311274

[21] Jiménez, C., Barra, M., Valls, S., Aponte, D., Vázquez, E. "Durability of recycled aggregate concrete designed with the Equivalent Mortar Volume (EMV) method: Validation under the Spanish context and its adaptation to Bolomey methodology", Materiales de Construcción, 64(313), Article ID: e006, 2014.
https://doi.org/10.3989/mc.2013.00913

[22] Kim, J. "Properties of recycled aggregate concrete designed with equivalent mortar volume mix design", Construction and Building Materials, 301, Article number: 124091, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.124091

[23] Abbas, A., Fathifazl, G., Fournier, B., Isgor, O. B., Zavadil, R., Razaqpur, A. G., Foo, S. "Quantification of the residual mortar content in recycled concrete aggregates by image analysis", Materials Characterization, 60(7), pp. 716–728, 2009.
https://doi.org/10.1016/j.matchar.2009.01.010

[24] JIS A 5021 "Recycled aggregate for concrete-class H", Japanese Standards Association, Japanese Industrial Standards, Tokyo, Japan, 2018.

[25] JIS A 5023 "Recycled aggregate for concrete-class L", Japanese Standards Association, Japanese Industrial Standards, Tokyo, Japan, 2018.

[26] Kim, J. "Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview", Construction and Building Materials, 328, Article number: 127071, 2022.
https://doi.org/10.1016/J.CONBUILDMAT.2022.127071

[27] Bai, G., Zhu, C., Liu, C., Liu, B. "An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties", Construction and Building Materials, 240, Article number: 117978, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117978

[28] Suryawanshi, S. R., Singh, B., Bhargava, P. "Characterization of recycled aggregate concrete", In: Matsagar, V. (ed.) Advances in Structural Engineering, Springer, New Delhi, India, 2015, pp. 1813–1822.
https://doi.org/https://doi.org/10.1007/978-81-322-2187-6_139

[29] Seo, D. S., Choi, H. B. "Effects of the old cement mortar attached to the recycled aggregate surface on the bond characteristics between aggregate and cement mortar", Construction and Building Materials, 59, pp. 72–77, 2014.
https://doi.org/10.1016/j.conbuildmat.2014.02.047

[30] Thomas, C., de Brito, J., Gil, V., Sainz-Aja, J. A., Cimentada, A. "Multiple recycled aggregate properties analysed by X-ray microtomography", Construction and Building Materials, 166, pp. 171–180, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.01.130

[31] Beauchemin, S., Fournier, B., Duchesne, J. "Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates", Cement and Concrete Research, 104, pp. 25–36, 2018.
https://doi.org/10.1016/j.cemconres.2017.10.008

[32] Geng, Y., Wang, Y., Chen, J. "Creep behaviour of concrete using recycled coarse aggregates obtained from source concrete with different strengths", Construction and Building Materials, 128, pp. 199–213, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.10.086

[33] Butler, L., West, J. S., Tighe, S. L. "The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement", Cement and Concrete Research, 41(10), pp. 1037–1049, 2011.
https://doi.org/10.1016/j.cemconres.2011.06.004

[34] Braymand, S., Roux, S., Fares, H., Déodonne, K., Feugeas, F. "Separation and Quantification of Attached Mortar in Recycled Concrete Aggregates", Waste and Biomass Valorization, 8, pp. 1393–1407, 2017.
https://doi.org/10.1007/s12649-016-9771-2

[35] de Juan, M. S., Gutiérrez, P. A. "Study on the influence of attached mortar content on the properties of recycled concrete aggregate", Construction and Building Materials, 23(2), pp. 872–877, 2009.
https://doi.org/10.1016/j.conbuildmat.2008.04.012