

EFFECTS OF PARTICLE SIZE AND TYPE OF AGGREGATE ON MECHANICAL PROPERTIES AND ENVIRONMENTAL SAFETY OF UNBOUND ROAD BASE AND SUBBASE MATERIALS: A LITERATURE REVIEW

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ABSTRACT: Unbound graded aggregates are used to construct the base and subbase of road pavement. The mechanical properties of unbound graded aggregates depend significantly on aggregate size and grading, especially on the maximum particle size ($D_{\max}$) and fines content (F_c ; typically, the particle size of fines < 0.075 mm). Nowadays, not only natural aggregates (NA) but also recycled aggregates (RA) from construction and demolition waste are used in road construction. Many studies have been done to characterize the mechanical properties of RA, but a comprehensive understanding of the effects of aggregate size and grading on the mechanical properties has not been fully achieved due to the wide variety of material types and properties of RA. Therefore, this paper searched previous studies and reviewed the effects of particle size, type of aggregate, and mixing proportions of RA on mechanical properties such as compaction, bearing capacity, resilient modulus, and shear strength. In addition, some information on the environmental safety of RA, such as leachate pH and leaching of elements, are summarized. The results collected from the literature indicate that the mechanical properties of RA and their mixtures are mostly comparable to those of NA and can be used to construct road base and subbase. As well as the type of aggregate, $D_{\max}$ of RA was also found to affect highly the relationships between the mechanical indices (e.g., the maximum dry density and California bearing ratio) and F_c and/or mixing proportion.

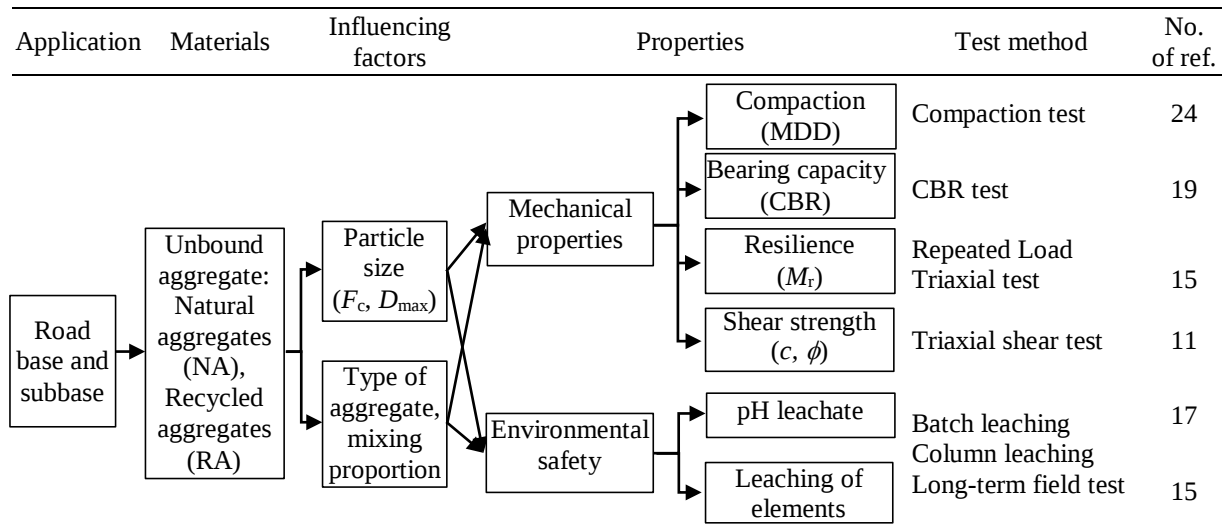
Keywords: *Unbound Road Base and Subbase, Recycled Aggregate, Construction and Demolition Waste, Mechanical Properties, Environmental Safety*

1. INTRODUCTION

Nowadays, not only crushed aggregates from natural stones (NA; natural aggregates) but also many kinds of recycled aggregates (RA) from construction and demolition waste (CDW) and industrial by-products (IBPs) are used as unbound road base and subbase materials in road construction [1,2]. The use of CDW and IBPs for road construction is one way to reduce the dumping of CDW and IBPs and to reduce the consumption of NA. However, there are some difficulties in recycling CDW and IBPs for civil engineering purposes because the types and qualities of RA affect the mechanical properties significantly. The base and subbase layers are important layers in the road pavement structure; they are required to have high rigidity and strength to bear the vertical load transmitted from the surface layers. In addition, the base and subbase layers of the pavement structure are usually made of unbound aggregates due to the low impact of the horizontal load. For example, Yoder and Witczak [3] reported that the stability and mechanical properties of unbound aggregate depend on several factors such as particle size distribution (grading), particle shape, relative density, internal friction, and cohesion. Among these factors, the size distribution of aggregate including the fines content

(F_c , kg/kg in %; typically, the particle size of fines < 0.075 mm) affected it the most. Xiao et al. [4] investigated the effect of particle size distribution on mechanical properties, permeability, frost susceptibility, and susceptibility to erosion and indicated that F_c needs to be controlled to meet the technical requirements that ensure the ability to function properly during construction and to improve the performance and longevity of a pavement structure.

Using RA from CDW and IBPs as road base and subbase materials has also an issue that needs to be considered, that is, environmental safety against surrounding environments and ecosystems. Leachate from RA often has a high pH that adversely affects groundwater resources and ecosystems at surface drainage locations [5]. In road construction, highly alkaline leachate often causes corrosion of zinc-galvanized and, particularly, aluminized pipes placed under the road (e.g., water supply and drainage pipes). An environment with a high pH will disrupt the aluminum oxide protective layers, thereby exposing the inner metal layers (aluminum, iron) and causing further corrosion [6]. Moreover, if RA from CDW and IBPs contains hazardous compounds, leached elements, including heavy metals and hazardous compounds, may pollute the surrounding soil and



MDD: Maximum dry density, CBR: California Bearing Ratio, M_r : Resilient modulus, c : Cohesion, ϕ : Friction angle

Fig.1 A process of reference selection for the review in this study

water. Therefore, the heavy metals and hazardous compounds extracted from RA should be tested and must be less than the specified environmental standards allow before the application of RA for road base and subbase construction.

Till now, many studies have been done to characterize the mechanical properties of RA, but a comprehensive understanding of the effects of aggregate size and grading on the mechanical properties has not been fully achieved due to the wide

variety of material types and properties of RA. Thus, this paper concentrated on reviewing and summarizing previous studies to examine the effects of particle size and grading (i.e., F_c , and the maximum particle size, D_{max}), and type of aggregate (i.e., materials used and mixing proportions) on the mechanical properties of unbound road base and subbase layers. Besides, some information on the environmental safety of RA, such as leachate pH and leaching of elements, are summarized.

Table 1 Abbreviations and definitions of materials in this study

Name	Abbreviation	Definition
Natural aggregate	NA	NA is aggregate crushed from natural stones (e.g., limestone, dolomite, granite, etc.)
Recycled concrete	RC	RC has a minimum of 90%, by mass, of Portland cement-based fragments and NA [7].
Recycled clay brick	RCB	RCB has mainly contained brick rubble and also a high amount of adhered mortar and other impurities such as tile [8].
Reclaimed asphalt pavement	RAP	RAP has more than 90% of the composition composed of asphalt-based materials [7].
Recycled glass	RG	RG is the by-product of crushing mixed color bottles and other glass products collected from both municipal and industrial waste streams [9].
Waste rock	WR	WR is excavated during site preparation, they would have been disposed of as waste [9].
A mixture of natural aggregate and recycled clay brick	NA-RCB	NA-RCB is a material made up of mixing natural aggregate and recycled clay brick in %.
A mixture of natural aggregate and reclaimed asphalt pavement	NA-RAP	NA-RAP is a material made up of mixing natural aggregate and reclaimed asphalt pavement in %.
A mixture of recycled concrete and recycled clay brick	RC-RCB	RC-RCB is a material made up of mixing recycled concrete and recycled clay brick in %.
A mixture of recycled concrete and reclaimed asphalt pavement	RC-RAP	RC-RAP is a material made up of mixing recycled concrete and reclaimed asphalt pavement in %.

2. METHODOLOGY

Based on keywords such as unbound aggregate, road base and subbase, aggregate size, fines content, and CDW materials, journal papers, books, and reports published in English since the 1970s were searched [e.g., Web of ScienceTM (Clarivate Analytics)]. A detailed search of the classifications was conducted to find references related to the effects of particle size and type of aggregates on mechanical properties such as compaction, bearing capacity, resilient modulus, and shear strength properties, and environmental safety of unbound aggregate for road base and subbase. The process of reference selection is shown in Fig.1. A total of 67 references was selected to compare and summarize the data. Abbreviations and definitions of materials used in this study are summarized in Table 1.

3. RESULTS AND DISCUSSION

3.1 Effects of Particle Size and Type of Aggregates on Mechanical Properties

3.1.1 Compaction characteristics

The maximum dry density (MDD) measured by the compaction test [10-11] is one of the factors to evaluate the effects of particle size and type of aggregate on compaction characteristics. The relationship between F_c and MDD is shown in Fig. 2, categorized as $D_{max} \leq 25\text{mm}$ and $D_{max} > 25\text{mm}$ categories. It is noted that most NA had higher MDD values than RA regardless of D_{max} and F_c because NA is less porous and has a higher particle density than RA [8]. For $D_{max} \leq 25\text{mm}$, not only NA but also other RA samples, MDD tended to increase with increasing F_c (Fig. 2a). On the other hand, MDD of NA became almost constant and showed a slight decrease with increasing F_c for $D_{max} > 25\text{mm}$ (Fig. 2b). These different trends might be attributed to the replacement of coarse aggregate pores with fines aggregates for $D_{max} \leq 25\text{mm}$ and to the intrinsic particle strength of RA and particle breakage (resulting in the cushion effect due to filled fines) for $D_{max} > 25\text{mm}$ [8]. Especially, it is understandable that the tested samples with high F_c of coarser aggregates ($D_{max} > 25\text{mm}$) enhanced the cushion effect more during the compaction process and resulted in no increment of MDD.

Measured MDDs for mixed aggregates, RC-RCB, RC-RAP, NA-RCB, and NA-RAP, are shown in Fig. 3 as a function of RC and/or NA content (%). In general, the measured MDD showed a gradual increase with increased proportion for both $D_{max} \leq 25\text{mm}$ (Fig. 3a) and $D_{max} > 25\text{mm}$ (Fig. 3b), whereas some data from RC-RCB and RC-RAP mixtures did not show any increment [30-32]. The differences in measured MDD values among tested samples were

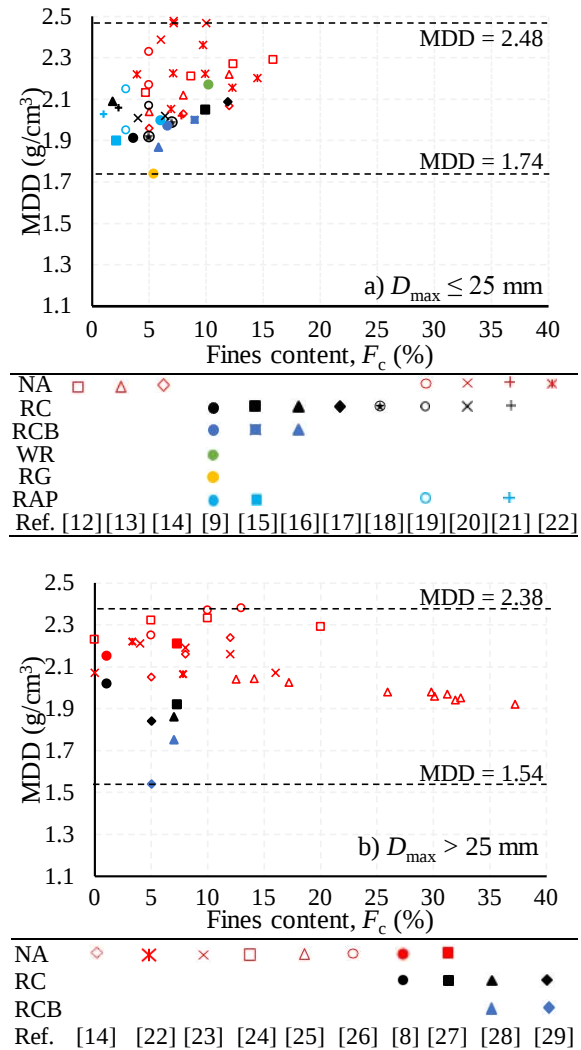


Fig.2 The effects of fines content and type of aggregate on MDD. (a) Samples with $D_{max} \leq 25\text{mm}$, and (b) samples with $D_{max} > 25\text{mm}$

caused mainly by the composition of mixtures, and a higher proportion of RC and/or NA increased MDD [16, 31, 33]. Notably, the measured MDDs of RC-RCB mixtures with $D_{max} \leq 25\text{mm}$ (Fig. 3a) were higher than those of RC-RCB mixtures with $D_{max} > 25\text{mm}$ (Fig. 3b). This might be because the larger aggregates of RCB were more breakable during the compaction process and resulted in lower MDD.

3.1.2 Bearing capacity

Effects of F_c and type of aggregate on CBR are shown in Fig. 4. It is reported that measured CBR values of recycled materials, RC, RCB, and WR, were higher than those of NA for both $D_{max} \leq 25\text{mm}$ (Fig. 4a) and $D_{max} > 25\text{mm}$ (Fig. 4b). This can be supposed to be because existing cementitious particles with RC and adhesive mortar on the surface of RCB would be hydrated and contributed to the increase in the aggregate bonding of samples [7].

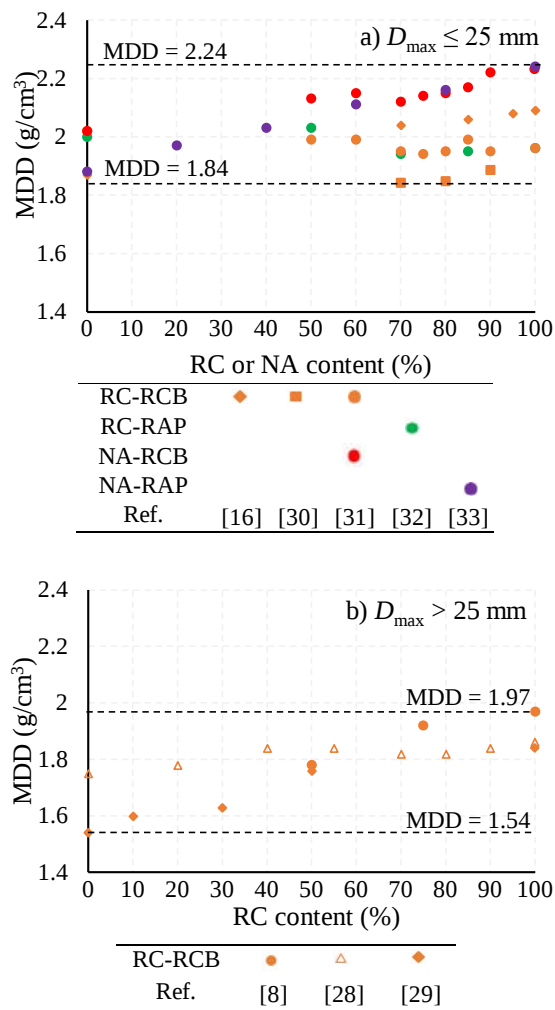


Fig. 3 The effects of mixing proportion on MDD. (a) Samples with $D_{\max} \leq 25$ mm, and (b) samples with $D_{\max} > 25$ mm

It can be seen that F_c contributed to the increase in CBR of NA for $D_{\max} \leq 25$ mm (Fig. 4a). In contrast, F_c decreased CBR of NA for $D_{\max} > 25$ mm (Fig. 4b). It was notable that RG and RAP gave the lowest CBR in comparison with other materials regardless of $D_{\max}$ and did not meet the technical requirement for road base and subbase (typically, $\text{CBR} \geq 80$ for road base, $\text{CBR} \geq 30$ for road subbase). This may be due to the small friction between the asphalt-coated aggregates, and RG aggregates, RG and RAP samples were found to slide easily and had low bearing capacity under the large load of the CBR test. Effects of the mixing proportion of RC or NA to RCB on CBR values are shown in Fig. 5. Except for some data, RC-RCB and NA-RCB exceeded mostly $\text{CBR} = 80\%$, and there was no significant relationship between measured CBR values and the mixing proportion for both $D_{\max} \leq 25$ mm (Fig. 5a) and $D_{\max} > 25$ mm (Fig. 5b). On the other hand, it can be seen that the CBR of RAP was improved by the mixing of RC or NA (Fig. 5a).

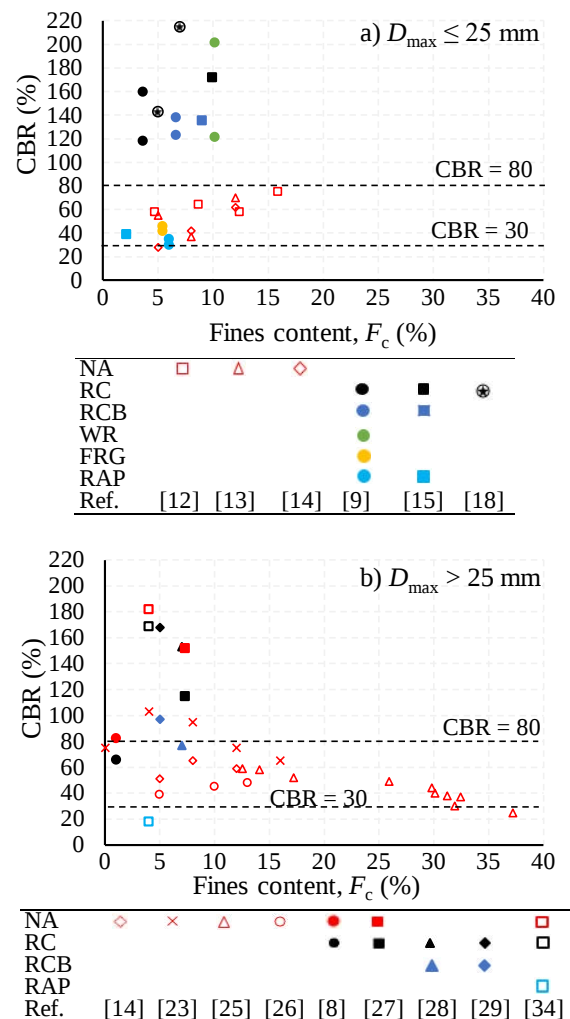


Fig. 4 The effects of fines content and type of aggregate on CBR. (a) Samples with $D_{\max} \leq 25$ mm, and (b) samples with $D_{\max} > 25$ mm

3.1.3 Resilience characteristic

Resilient modulus (M_r) is an index representing the resilience of the unbound material under repeated traffic loading. M_r is defined as the ratio of the cycle deviator stress to the recoverable strain and is determined by repeated load compression tests of test specimens. The reported results of M_r for various RA samples are summarized in Table 2. In general, there were three trends of M_r of NA samples; M_r increased when F_c increased [35], M_r decreased when F_c increased [36], and M_r reached the highest value at a F_c value [24, 37], indicating that the tendency of M_r according to F_c was not consistent in previous studies. It may be because M_r depends not only on F_c but also on other factors such as single-particle strength, particle breakage, particle shape, etc. In terms of the effect of $D_{\max}$ on M_r , Mneina and Shalaby [22] studied NA samples with three different $D_{\max}$ values and found that M_r increased when $D_{\max}$ increased, suggesting that the increase in M_r could be gained in

the coarser aggregate frame structure due to a better grain contact.

As shown in Table 2, several researchers reported that M_r values of RC were higher than those of NA [9, 20-21, 38-39], and satisfied the technical requirement [18]. This could be explained by the contribution of several cementitious particles inside RC to increasing the strength of RC samples by hydration [7, 9]. It is important to point out that the reported M_r values of various RA samples were highly dependent on the tested materials. For example, Arulrajah et al. [9] submitted that the M_r values for RAP and RG could not be reported because they had very low cohesion, and their samples failed after a few loading cycles of the test. On the other hand, Nokkaew [21] indicated that RAP had higher M_r than RC and NA because RAP was obtained from asphalt layers which were usually constructed from higher quality aggregate than RC. Turning to the mixtures, Arulrajah et al. [32] reported that CB-RC mixtures had higher M_r values than CB-NA and most the mixtures would perform satisfactorily as a subbase material. Arisha et al. [28] showed that the M_r of RCB-RC blends was highest with the sample using 45% RCB, while Cameron et al. [30] indicated that M_r of RCB-RC blends decreased when RCB content increased. M_r of NA-RAP mixtures increased with the increase of RAP content [19, 40]

3.1.4 Shear strength properties

Shear strength properties of RA are mostly assessed by triaxial tests, and the cohesion (c in kPa) and friction angle [ϕ in degrees ($^\circ$)] of the tested specimen were determined based on Mohr-Coulomb failure criteria. Table 3 summarizes the reported c and ϕ values of RA. The measured c and ϕ varied depending on the tested materials but the c values generally ranged between 40 kPa and 90 kPa and measured ϕ ranged between 20° and 50° , and which were similar to the measured values of NA. Some researchers reported that shear strength peaked at the highest when $F_c = 8\text{--}10\%$ [24, 42]. This can be explained by the structural change of the aggregates along with F_c [3, 43]; shear strength is based on grain-to-grain contact with the samples containing little or no F_c . Under the condition of sufficient F_c in the tested sample, the fines fill the voids between the grains and bind them together. This combines grain-to-grain contact to increase the shear strength of samples. However, with samples containing high F_c , the grains are surrounded by fines, grain-to-grain contact will be reduced significantly, and the shear strength will decrease and depend on the shear strength of fines. On the other hand, Osouli et al. [13] studied crushed stone aggregates of $D_{\max} = 25$ mm using two values of F_c (5% and 12%) and reported that shear strength properties were not affected by the quality of F_c , $c = 70$ kPa and $\phi = 41^\circ$ for both samples.

This suggests that further studies are needed to examine the effects of F_c and $D_{\max}$ on the shear strength properties of RA.

3.2 Environmental Safety of Recycled Aggregates

3.2.1 Leachate pH

In a comparison of pH of NA and RA leachates, RC leachate had the highest pH (normal $\text{pH} > 10$), while NA was below pH 9 [5, 47], RCB was neutral or slightly alkaline (pH from 8.04 to 8.48) [48]. This is because RA from CDW usually includes cement, and the mortar adheres to the surface of aggregates. These compounds are composed of many chemicals of calcium-silicate-aluminate that will be hydrated in an aqueous solution to produce $\text{Ca}(\text{OH})_2$ with high alkalinity [47]. Sanger et al. (2020) [49] showed a good summary of leachate pH determined in the field and laboratory. The measured pH of RC leachates was 9.9–13 [5, 20, 50–59] in a batch leaching test and 10.8–12.5 [60] in a column leaching test. Regarding the long-term field tests of pH, some authors pointed out that the leachate from RC had a high pH in the early stages of the test, and that the pH value gradually decreased to neutral after a few years. Specifically, Chen et al. [60] reported a pH of RC leachate between 6.5 and 8.0 at seven years after construction; the final leachate measured pH 7.2 to 7.4 after eight years [50], and the pH of RC leachate measured from the base course with asphalt-covered section was consistently between 7.3 and 8.7 after more than ten years of field monitoring [61].

Lee et al. [47] measured the pH of RA and reported that fine aggregates (less than 5 mm) initially had a high pH and that the pH did not change much during the experiment, while coarse aggregates (more than 5 mm) had a low initial pH, but the pH increased during the elution time and reached a pH similar to the pH measured for fines aggregate. In addition, Lee et al. reported that NA had a similar pH (below pH 9) for both fine and coarse aggregates [47].

3.2.2 Leaching of elements

Total elemental analysis of RA from CDW has demonstrated the presence of aluminum (Al), arsenic (As), boron (B), barium (Ba), calcium (Ca), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), tin (Sn), strontium (Sr), titanium (Ti), vanadium (V), zinc (Zn), chloride (Cl^-), fluoride (F^-), sulfate (SO_4^{2-}), and organic compounds (phenol index) [5, 48, 51–54, 60, 62–64]. Lee et al. [47] reported that although RA had more harmful substances than NA, their leachates had concentrations of elements below the limits mentioned in the environmental standards, and RA from CDW were classified as inert or non-hazardous

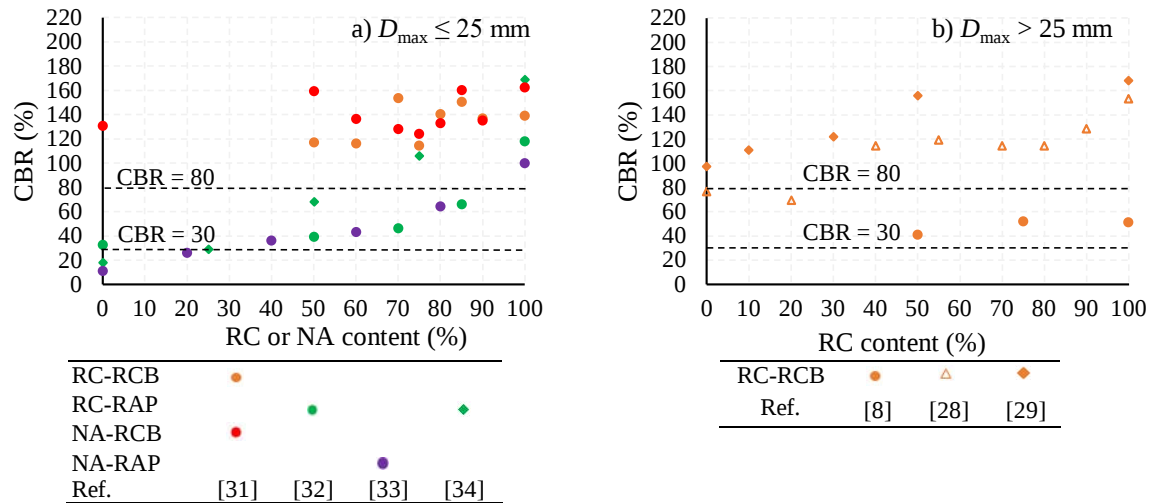


Fig. 5 The effects of the mixing proportion on CBR. (a) Samples with $D_{\max} \leq 25$ mm, and (b) samples with $D_{\max} > 25$ mm

Table 2 Effects of type of aggregates and particle size on resilience characteristic

Materials	Mixing proportion** (%)	Range of F_c (%)	$D_{\max}$ (mm)	Test method and specimen size (D x H, mm)	Effects on M_r	Ref.
NA, RC, RAP	NA-RAP: 50-50, 25-75 RC-RAP: 50-50, 25-75	*	25	AASHTO T307 152 x 304	M_r increased as the RAP content increased, NA\RC-RAP blends had higher M_r than NA\RC.	[19]
NA, RC	*	*	25	AASHTO T307 152 x 304	M_r of RC was up to 2.6 times higher than that of NA	[20]
NA, RC, RAP	*	*	19	NCHRP 1-28A 152 x 304	M_r of NA was lower than that of RA. RAP had higher M_r than RC	[21]
NA	*	*	19, 25, 37.5	NCHRP 1-28A 100 x 200	M_r increased when $D_{\max}$ increased	[22]
NA	*	0 - 20	31.75	AASHTO T307	M_r was highest with $F_c=5\%$ and lowest with $F_c=10\%$	[24]
RC, RCB	RC-RCB: 100-0, 90-10, 80-20, 70-30, 55-45, 40-60, 20-80, and 0-100	*	37.5	AASHTO T307 152 x 304	M_r was the highest with the sample using 45% RCB	[28]
RC, RCB	RC-RCB: 90-10, 80-20, 70-30	*	20	DTEI -TP183 (2008)	M_r decreased with the increase of RCB content	[30]
RC, RCB, NA	RCB-RC\NA: 0-100, 15-85, 20-80, 25-75, 30-70, 40-60, and 50-50	*	20	Austroroads (2000) 100 x 200	CB-RC blends had higher M_r values than CB-NA blends.	[31]
NA	*	7 - 12	*	AASHTO T292-1998	M_r increased with the increase of F_c	[35]
NA	*	0 -17.7	25	AASHTO T307 152 x 304	M_r decreased with the increase of F_c	[36]
NA	*	2 - 14	38.1	AASHTO T307 152 x 304	M_r reached highest with $F_c = 6-10\%$	[37]
RC	*	*	20	Austroroads (2004) 100 x 200	RC had higher M_r than NA	[38]
RC, NA	*	*	20	Austroroads (2004) 100 x 200	RC had higher M_r than NA	[39]
RAP, NA	RAP-NA: 0-100, 25-75, 50-50, 75-25	*	20	NCHRP 1-28A 152 x 304	M_r increased as the RAP content increased	[40]
RC, CB, WR	*	*	20	Austroroads (2004) 100 x 200	RC had the highest M_r value and WR had the lowest M_r value	[41]

D: Diameter in mm, H: Height in mm of the cylindrical specimen

*Data not available, **A-B means a mixture of material A and material B in %; A\B means material A or material B.

Table 3 Effects of type of aggregates and particle size on shear strength properties

Materials	Mixing proportion** (%)	Range of F_c (%)	D_{max} (mm)	Test method and specimen size (D x H, mm)	Effect on shear strength properties (c in kPa, ϕ in °)	Ref.
RC, CB, WR, RAP, RG	*	*	20	ASTM D4767-04, CD triaxial, 100 x 200	RC, CB, WR: $c = 41 - 46$ kPa, $\phi = 49 - 51^\circ$ RG, RAP: $c = 0$, 53 kPa, $\phi = 37^\circ$	[9]
NA	*	5, 12	25	ASTM D2850, UU triaxial, 152 x 304	$c = 70$ kPa, $\phi = 41^\circ$	[13]
RC, RCB, RAP	*	*	20	CD triaxial tests, 100 x 200	$c = 45.4 - 66.4$ kPa, $\phi = 51 - 58^\circ$	[15]
RC, RCB, WR	RCB-RC\WR: 0-100, 15-85, 20-80, 25-75, 30-70, 40-60, 50-50	*	20	ASTM D4767-04 CD triaxial, 100 x 200	RCB-RC: $c = 41 - 80$ kPa, $\phi = 43 - 50^\circ$ RCB-WR: $c = 41 - 62$ kPa, $\phi = 46 - 51^\circ$	[31]
RC	*	*	20	ASTM D4767-04, CD triaxial, 100 x 200	$c = 45$ kPa, $\phi = 49^\circ$	[38]
NA	*	1.5-10.5	25	* 152 x 304	Shear strength was highest when F_c was approximately 8%	[42]
NA	*	0-20	50	ASTM D4767-04, CD triaxial, 300 x 600	ϕ decreased with the increase of F_c	[43]
NA	*	1.5-11.7	25	* 152 x 304	$c = 0 - 121.4$ kPa, $\phi = 23.6 - 54.4^\circ$	[44]
RC, RCB	RC-RCB: 80-20	*	20	AS 1289.6.4.1, UU triaxial, 100 x 200	$c = 9 - 89$ kPa, $\phi = 44 - 56^\circ$	[45]
NA	*	*	25	* 152 x 304	$c = 1.1 - 85.1$ kPa, $\phi = 45 - 51^\circ$	[46]

c: Cohesion, ϕ : Friction angle, UU: Unconsolidated undrained, CD: Consolidated drained, D: Diameter in mm, H: Height in mm of the cylindrical specimen.

*Data not available. **A-B means a mixture of material A and material B in %; A/B means material A or material B.

waste [48, 62, 64-66]. However, it has been reported that the leaching of elements was dependent on particle size. For example, Bestgen et al. [20] reported that the leached metal concentrations increased when the particle size decreased. Diffusion is a major cause of metal leaching [67], and the higher total surface area of the grading with a high content of small particle sizes would increase the interaction between particles and extraction solution, and thus enhance diffusion, metal leaching. Therefore, the extraction of heavy metals and hazardous compounds from RA should be tested and must be lower than the specified environmental standards before the application to the road base and subbase construction.

4. CONCLUSIONS

Based on the results of literature reviews, some conclusions could be drawn:

1) Generally, the RA samples with $D_{max} \leq 25$ mm gave higher MDD and CBR than samples with D_{max}

> 25 mm. RC, RCB, WR, and RC-RCB mixtures had lower MDD than NA but their CBR were comparable to or higher than NA and satisfied the technical requirement for road base and subbase. On the other hand, the CBR values of RAP and RG became small and did not meet the technical requirements, so it is important to mix them with higher quality aggregates such as NA and RC.

2) Due to the hydration of the remaining unhydrated cement particles in RC, M_r values of RC and RC-RCB mixtures became higher than those of NA and NA-RCB and they met the technical requirements for road base and subbase. The shear strength of unbound materials usually reaches the highest value at a certain value of F_c . Most RA samples and their mixtures had equivalent c and ϕ values in comparison with NA samples.

3) The leachate pH of RA is often higher than that of NA and the high pH continues for many years after its application in construction. Because the leaching of elements from RA was dependent on the particle size, the concentration of heavy metals and

hazardous compounds extracted from RA should be tested before its application to road base and subbase construction.

Finally, based on the review of previous studies, F_c and D_{max} and type of aggregate affected the mechanical properties of unbound road base and subbase materials. However, other factors such as particle shape, single-particle strength, particle breakage, compaction energy effort, etc. also affect the mechanical properties. In addition, not only static but also dynamic mechanical properties should be examined for various types of RA. Further studies are needed to understand the combined effects on the mechanical properties of unbound road base and subbase materials.

5. ACKNOWLEDGMENTS

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6. REFERENCES

- [1] Deloitte, Resource Efficient Use of Mixed Wastes Improving management of construction and demolition waste, 2017.
- [2] MLIT, White paper on land, infrastructure, transport and tourism in Japan, 2017.
- [3] Yoder E. and Witzczak M.W., Principles of Pavement Design, Second Edition, 1975, pp. 1–711.
- [4] Xiao Y., Tutumluer E., Qian Y., and Siekmeier J., Gradation effects influencing mechanical properties of aggregate base-granular subbase materials in Minnesota, *Transp. Res. Rec.*, no. 2267, 2012, pp. 14–26.
- [5] Gupta N., Kluge M., Chadik P.A., and Townsend T.G., Recycled concrete aggregate as road base: Leaching constituents and neutralization by soil Interactions and dilution, *Waste Manag.*, vol. 72, 2018, pp. 354–361.
- [6] Akhoondan M. and Sagues A.A., Corrosion of aluminized steel in aggressive natural water, *ECS Trans.*, vol. 45, no. 19, 2013, pp. 25–35.
- [7] Cardoso R., Silva R.V., Brito J., and Dhir R., Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review, *Waste Manag.*, vol. 49, 2016, pp. 131–145.
- [8] Poon C.S. and Chan D., Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base, *Constr. Build. Mater.*, vol. 20, no. 8, 2006, pp. 578–585.
- [9] Arulrajah A., Piratheepan J., Disfani M.M., and Bo M.W., Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications, *J. Mater. Civ. Eng.*, vol. 25, no. 8, 2013, pp. 1077–1088.
- [10] ASTM D1557, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)), West Conshohocken, PA, USA, 2003.
- [11] AASHTO T180, Standard Method of Test for Moisture–Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop, Washington, DC.
- [12] Mishra D., Tutumluer E., and Butt A.A., Quantifying effects of particle shape and type and amount of fines on unbound aggregate performance through controlled gradation, *Transp. Res. Rec.*, no. 2167, 2010, pp. 61–71.
- [13] Osouli A., Salam S., and Tutumluer E., Effect of plasticity index and dust ratio on moisture-density and strength characteristics of aggregates, *Transp. Geotech.*, vol. 9, 2016, pp. 69–79.
- [14] Chaulagai R., Osouli A., Salam S., Tutumluer E., Beshears S. Shoup H., and Bay M., Influence of maximum particle size, fines content, and dust ratio on the behavior of base and subbase coarse aggregates, *Transp. Res. Rec.*, vol. 2655, 2017, pp. 20–26.
- [15] Rahman M. A., Imteaz M., Arulrajah A., and Disfani M.M., Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials, *J. Clean. Prod.*, vol. 66, 2014, pp. 75–84.
- [16] Diagne M., Tinjum J.M., and Nokkaew K., The effects of recycled clay brick content on the engineering properties, weathering durability, and resilient modulus of recycled concrete aggregate, *Transp. Geotech.*, vol. 3, 2015, pp. 15–23.
- [17] Kien T.T., Thanh L.T., and Lu P.V., Utilisation of construction demolition waste as stabilised materials for road base applications, *Int. Conf. on Sustainable Built Environment for Now and the Future*, 2013, pp. 285–293.
- [18] Gabr A.R. and Cameron D.A., Properties of recycled concrete aggregate for unbound pavement construction, *J. Mater. Civ. Eng.*, vol. 24, no. 6, 2012, pp. 754–764.
- [19] Arshad M. and Ahmed M.F., Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pavements, *Constr. Build. Mater.*, vol. 151, 2017, pp. 83–97.
- [20] Bestgen J.O., Hatipoglu M., Cetin B., and Aydilek A.H., Mechanical and environmental suitability of recycled concrete aggregate as a highway base material, *J. Mater. Civ. Eng.*, vol. 28, no. 9, 2016, p. 04016067.
- [21] Nokkaew K., Characterization of recycled aggregate for use as base course material, *Int. J. Geomate*, vol. 15, no. 48, 2018, pp. 129–136.

- [22] Mneina A. and Shalaby A., Relating gradation parameters to mechanical and drainage performance of unbound granular materials, *Transp. Geotech.*, vol. 23, no. July 2019, 2020, p. 100315.
- [23] Siswosoebrotho B.I., Widodo P., and Augusta E., The influence of fines content and plasticity on the strength and permeability of aggregate base Class A, *Proceedings of the Eastern Asia Society for Transp. Studies*, vol. 5, 2000, pp. 845–856.
- [24] Gandara J.A., Kancherla A., Alvarado G., Nazarian S., and Scullion T., TX-0-4358-2 Impact of aggregate gradation on base material performance, 2005, pp. 1–63.
- [25] Inan I.I.I., Mampearachchi W.K., and Udayanga P.A.S., Effect of fine percentage on the properties of sub-base material, *Eng. J. Inst. Eng. Sri Lanka*, vol. 49, no. 4, 2016, p. 15.
- [26] Fattah M.Y., Hilal M.M., and Flyeh H.B., Effect of fine material on compaction characteristics of subbase material using the Superpave Gyratory Compactor, *Int. J. Civ. Eng. Technol.*, vol. 7, no. 5, 2016, pp. 466–476.
- [27] Jiménez J.R., Agrela F., Ayuso J., and López M., A comparative study of recycled aggregates from concrete and mixed debris as material for unbound road sub-base, *Mater. Constr.*, vol. 61, no. 302, 2011, pp. 289–302.
- [28] Arisha A.M., Gabr A.R., El-Badawy S.M., and Shwally S.A., Performance evaluation of construction and demolition waste materials for pavement construction in Egypt, *J. Mater. Civ. Eng.*, vol. 30, no. 2, 2018, p. 04017270.
- [29] Tran V.C., Nguyen V.T., Nguyen H.G., and Kawamoto K., Utilization of construction and demolition waste (CDW) for unbound road subbase in Hanoi, Vietnam, *Lect. Notes Civ. Eng.*, vol. 62, 2020, pp. 731–735.
- [30] Cameron D.A., Azam A.H., and Rahman M.M., Recycled clay masonry and recycled concrete aggregate blends in pavement, *Geotech. Spec. Publ.*, no. 225 GSP, 2012, pp. 1532–1541.
- [31] Arulrajah A., Piratheepan J., Bo M.W., and Sivakugan N., Geotechnical characteristics of recycled crushed brick blends for pavement sub-base applications, *Can. Geotech. J.*, vol. 49, no. 7, 2012, pp. 796–811.
- [32] Arulrajah A., Piratheepan J., and Disfani M.M., Reclaimed asphalt pavement and recycled concrete aggregate blends in pavement subbases: Laboratory and field evaluation, *J. Mater. Civ. Eng.*, vol. 26, no. 2, 2014, pp. 349–357.
- [33] Taha R., Ali G., Basma A., and Al-Turk O., Evaluation of reclaimed asphalt pavement aggregate in road bases and subbases, *Transp. Res. Rec.*, no. 1652, 1998, pp. 264–269.
- [34] Bennert T.A. and Maher A., The use of recycled concrete aggregate in a dense graded aggregate base course, 2008, pp. 1–65.
- [35] Khogali W.E.I. and Elhussein H.M., Novel approach for characterization of unbound materials, *Transp. Res. Rec.*, vol. 1874, 2004, pp. 38–46.
- [36] Richardson D. and Lusher S.M., Resilient moduli of granular base materials using a modified type 5 gradation, 2009, pp. 1–40.
- [37] Hatipoglu M., Cetin B., and Aydilek A.H., Effects of fines content on hydraulic and mechanical performance of unbound granular base aggregates, *J. Transp. Eng. Part B Pavements*, vol. 146, no. 1, 2020, pp. 1–20.
- [38] Arulrajah A., Piratheepan J., Ali M.M.Y., and Bo M.W., Geotechnical properties of recycled concrete aggregate in pavement sub-base applications, *Geotech. Test. J.*, vol. 35, no. 5, 2012, pp. 1–9.
- [39] Gabr A.R., Mills K.G., and Cameron D.A., Repeated load triaxial testing of recycled concrete aggregate for pavement base construction, *Geotech. Geol. Eng.*, vol. 31, no. 1, 2013, pp. 119–132.
- [40] Kim W., Labuz J.F., and Dai S., Resilient modulus of base course containing recycled asphalt pavement, *Transp. Res. Rec.*, no. 2005, 2007, pp. 27–35.
- [41] Arulrajah A., Piratheepan J., Disfani M.M., and Bo M.W., Resilient moduli response of recycled construction and demolition materials in pavement subbase applications, *J. Mater. Civ. Eng.*, vol. 25, no. 12, 2013, pp. 1920–1928.
- [42] Qamhia I., Tutumluer E., Chow L.C., and Mishra D., A framework to utilize shear strength properties for evaluating rutting potentials of unbound aggregate materials, *Procedia Eng.*, vol. 143, 2016, pp. 911–920.
- [43] Chen X. and Zhang J., Effect of clay invasion on shear behavior and dilatancy of unbound aggregate subbase, *Transp. Geotech.*, vol. 6, 2016, pp. 16–25.
- [44] Byun Y.-H., Feng B., Qamhia I.I.A., and Tutumluer E., Aggregate properties affecting shear strength and permanent deformation characteristics of unbound–base course materials, *J. Mater. Civ. Eng.*, vol. 32, no. 1, 2020, p. 04019332.
- [45] Azam A.M. and Cameron D.A., Geotechnical properties of blends of recycled clay masonry and recycled concrete aggregates in unbound pavement construction, *J. Mater. Civ. Eng.*, vol. 25, no. 6, 2013, pp. 788–798.
- [46] Chow L.C., Mishra D., and Tutumluer E., Framework for development of an improved unbound aggregate base rutting model for mechanistic-empirical pavement design, *Transp. Res. Rec.*, no. 2401, 2014, pp. 11–21.

- [47] Lee J.C., Song T.H., and Lee S.H., Leaching behavior of toxic chemicals in recycled aggregates and their alkalinity, *J. Mater. Cycles Waste Manag.*, vol. 14, no. 3, 2012, pp. 193–201.
- [48] Saca N., Dimache A., Radu L.R., and Iancu I., Leaching behavior of some demolition wastes, *J. Mater. Cycles Waste Manag.*, vol. 19, no. 2, 2015, pp. 623–630.
- [49] Sanger M., Natarajan B.M., Wang B., Edil T., and Ginder-Vogel M., Recycled concrete aggregate in base course applications: Review of field and laboratory investigations of leachate pH, *Journal of Hazardous Materials*, vol. 385, 2020, pp. 121562.
- [50] Natarajan B.M., Kanavas Z., Sanger M., Rudolph J., Chen J., Edil T., and Ginder-Vogel M., Characterization of recycled concrete aggregate after eight years of field deployment, *J. Mater. Civ. Eng.*, vol. 31, no. 6, 2019, pp. 04019070.
- [51] Engelsen C.J., van der Sloot H.A., Wibetoe G., Petkovic G., Stoltenberg-Hansson E., and Lund W., Release of major elements from recycled concrete aggregates and geochemical modelling, *Cem. Concr. Res.*, vol. 39, no. 5, 2009, pp. 446–459.
- [52] Engelsen C.J., Van Der Sloot H.A., Wibetoe G., Justnes H., Lund W., and Stoltenberg-Hansson E., Leaching characterisation and geochemical modelling of minor and trace elements released from recycled concrete aggregates, *Cem. Concr. Res.*, vol. 40, no. 12, 2010, pp. 1639–1649.
- [53] Butera S., Christensen T.H., and Astrup T.F., Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds, *J. Hazard. Mater.*, vol. 276, 2014, pp. 302–311.
- [54] Coudray C., Amant V., Cantegrit L., LeBocq A., Thery F., Denot A., and Eisenlohr L., Influence of crushing conditions on recycled concrete aggregates (RCA) leaching behaviour, *Waste and Biomass Valorization*, vol. 8, no. 8, 2017, pp. 2867–2880.
- [55] Abbaspour A., Tanyu B.F., and Cetin B., Impact of aging on leaching characteristics of recycled concrete aggregate, *Environ. Sci. Pollut. Res.*, vol. 23, no. 20, 2016, pp. 20835–20852.
- [56] Bestgen J. O., Cetin B., and Tanyu B.F., Effects of extraction methods and factors on leaching of metals from recycled concrete aggregates, *Environ. Sci. Pollut. Res.*, vol. 23, no. 13, 2016, pp. 12983–13002.
- [57] Engelsen C.J., Wibetoe G., van der Sloot H.A., Lund W., and Petkovic G., Field site leaching from recycled concrete aggregates applied as sub-base material in road construction, *Sci. Total Environ.*, vol. 427–428, 2012, pp. 86–97.
- [58] Mulugeta M., Engelsen C.J., Wibetoe G., and Lund W., Charge-based fractionation of oxyanion-forming metals and metalloids leached from recycled concrete aggregates of different degrees of carbonation: A comparison of laboratory and field leaching tests, *Waste Manag.*, vol. 31, no. 2, 2011, pp. 253–258.
- [59] Sanchez F., Gervais C., Garrabarants A.C., Barna R., and Kosson D.S., Leaching of inorganic contaminants from cement-based waste materials as a result of carbonation during intermittent wetting, *Waste Manag.*, vol. 22, 2002, pp. 249–260.
- [60] Chen J., Tinjum J., and Edil T., Leaching of alkaline substances and heavy metals from recycled concrete aggregate used as unbound base course, *Transp. Res. Rec.*, no. 2349, 2013, pp. 81–90.
- [61] Engelsen C.J., van der Sloot H.A., and Petkovic G., Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction, *Sci. Total Environ.*, vol. 587–588, no. 2017, 2017, pp. 94–101.
- [62] Galvín A.P., Ayuso J., Agrela F., Barbudo A., and Jiménez J.R., Analysis of leaching procedures for environmental risk assessment of recycled aggregate use in unpaved roads, *Constr. Build. Mater.*, vol. 40, 2013, pp. 1207–1214.
- [63] Garrabrants A.C., Sanchez F., and Kosson D.S., Changes in constituent equilibrium leaching and pore water characteristics of a Portland cement mortar as a result of carbonation, *Waste Management*, vol. 24, no. 1, 2004, pp. 19–36.
- [64] Chen Y. and Zhou Y., The contents and release behavior of heavy metals in construction and demolition waste used in freeway construction, *Environ. Sci. Pollut. Res.*, vol. 27, no. 1, 2020, pp. 1078–1086.
- [65] Roussat N., Méhu J., Abdelghafour M., and Brula P., Leaching behaviour of hazardous demolition waste, *Waste Manag.*, vol. 28, no. 11, 2008, pp. 2032–2040.
- [66] Barbudo A., Galvín A.P., Agrela F., Ayuso J., and Jiménez J.R., Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes, *Waste Manag.*, vol. 32, no. 6, 2012, pp. 1229–1235.
- [67] Van Gerven T., Cornelis G., Vandoren E., and Vandecasteele C., Effects of carbonation and leaching on porosity in cement-bound waste, *Waste Manag.*, vol. 27, no. 7, 2007, pp. 977–985.