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Cold-Bonding Technique – A New Approach to Recycle Innocuous Construction Residual Soil, Sludge, and Sediment as Coarse Aggregates

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1. Introduction

This chapter mainly illustrates that the mechanism and process of cold-bonding technique as well as using of three various innocuous recycling resources, construction residual soil, granite sludge, and lime sludge, to produce recycling coarse aggregates through the cold-bonding technique.

1.1 Output and source of the innocuous recycling resources in Taiwan

The attention of shortage of the primitive aggregate has been received in Taiwan. Although the natural resource in Taiwan is rather lack, the innocuous recycling resources are quite plentiful (e.g., construction residual soil, granite sludge, lime sludge, reservoir sediments, and so on). Using above-mentioned resources to manufacture the recycling green building materials is a good means in light of several aspects, including the reduction of waste, recycling of resource, and low carbon society. The Taiwan government has been devoted to developing the sustainability of society and has promulgated some acts to achieve this goal (Hsieh et al., 2012). Certainly, use of above-mentioned resources is one of the crucial issues because the resources and space for storing waste in Taiwan is so limited. Moreover, the global warming (or so-called climate change) is one of hot issues, in which how to reduce CO_2 has received much attention.

For the promotion and facility of reuse and recycling of construction residual soil, which are generally sorted as 9 categories (i.e. B1 to B7) in Taiwan as shown in Table 1 (Industrial Technology Research Institute [ITRI], 1996). Herein the construction residual soils of B1, B2-1, B2-2, and B5 categories were immediately reused through uncomplicated process (like crushing and sieving, etc.), but the reuse rate of B2-3, B3, B4, B6, and B7 categories is extremely low due to their poor properties. According to the evaluation by the Construction and Planning Agency Ministry of the Interior, R.O.C. the construction residual soil of about 40 millions m^3 is generated every year as shown in Table 2, and the B2-3, B3, B4, B6, and B7 categories with extremely low reuse rate accounted for more than 50 %.

Code	Properties of construction residual soil
B1	Rocks, gravels, crushed rocks, or sand
B2-1	Blended soil, gravels, and sand (soil <30 % by vol.)
B2-2	Blended soil, gravels, and sand (30 %<soil<50 % by vol.)
B2-3	Blended soil, gravels, and sand (soil>50 % by vol.)
B3	Silt
B4	Clay
B5	Brick and concrete blocks
B6	Sediment or soil contains >30 % moisture by wt.
B7	Bentonite from continuous walls construction

Table 1. Categories of construction residual soil in Taiwan.

	B1 (m^3)	B2-1 (m^3)	B2-2 (m^3)	B2-3 (m^3)	B3 (m^3)	B4 (m^3)	B5 (m^3)	B6 (m^3)	B7 (m^3)	Total (m^3)
2002	9,745,339	3,157,653	2,660,776	3,859,634	6,253,732	4,641,081	286,941	175,606	131,461	30,912,223
2003	6,491,354	6,256,473	4,009,632	6,125,236	6,927,483	4,852,074	995,285	803,362	424,588	36,885,487
2004	4,109,131	8,417,495	6,705,485	6,530,775	8,408,148	5,177,942	809,651	612,185	107,955	40,878,767
2005	2,178,436	8,148,354	6,974,924	9,182,229	8,409,695	5,884,677	1,095,015	485,395	78,657	42,437,382
2006	1,749,982	7,975,805	6,272,035	9,352,248	7,340,871	5,571,844	1,370,277	917,939	46,155	40,597,156
2007	3,099,089	6,538,887	4,829,821	9,762,949	6,524,040	4,483,718	1,636,861	1,294,205	31,871	38,201,441
2008	3,079,980	7,420,172	4,499,688	8,924,265	6,560,130	3,821,069	1,895,799	538,005	55,848	36,794,956
2009	2,419,110	5,494,537	3,982,374	8,289,454	3,818,809	1,917,679	1,393,881	529,180	237,392	28,082,416
2010	1,862,649	5,984,624	3,840,541	11,238,137	3,732,365	2,533,991	1,653,261	948,366	680,717	32,474,651
Total	34,735,070	59,394,000	43,775,276	73,264,927	57,975,273	38,884,075	11,136,971	6,304,243	1,794,644	327,264,479
(%)	10.61	18.15	13.38	22.39	17.72	11.88	3.40	1.93	0.55	100.00

Table 2. Output of the construction residual soil every year in Taiwan (ITRI, 1996).

The granite sludge of about 300,000 to 500,000 ton was generated from cutting and grinding granite in Taiwan. The common treatment and final disposal technology of granite sludge were solidification and landfill in the past, therefore its recycling amount is only approximately 50,000 ton every year. The granite sludge should not be classified as an industrial waste, but rather a recycling resource. On the basis of environmental protection aspects and increase economic benefits, the cold-bonding technique was adopted to recycle granite sludge as coarse aggregates.

The China Petrochemical Development Corporation (CPDC) An-Shun site that was a decommissioned chloroalkaline and pentachlorophenol manufacturing plant in Tainan, Taiwan includes 115,000 m^3 of chloroalkaline plant, 40,000 m^3 of pentachlorophenol plant, 47,000 m^3 of vegetation area, 27,000 m^3 of grass area, and 155,000 m^3 of seawater storage pond as shown in Fig. 1 (Chao et al., 2008). The highest mercury concentration was found in the chloroalkaline plant with a level as high as 3,370 mg/kg in soil, way above the soil control standard of 20 mg/kg. The worst dioxin contamination was found in the pentachlorophenol plant with levels as high as 64,100,000 ng-I-TEQ/kg in soil, whereas the soil control standard is 1,000 ng-I-TEQ/kg. But there is a large amount of about 90,000 m^3 of uncontaminated and innocuous lime sludge in vegetation area. The CPDC expected to recycle the above-mentioned uncontaminated and innocuous lime sludge as recycling coarse aggregates through using cold-bonding technique for the remediation and reconstruction of CPDC An-Shun site in the future.

Fig. 1. The surrounding location of CPDC An-Shun site (Chao et al., 2008).

1.2 Mechanism of cold-bonding technique

Based on the purposes of green building materials (i.e. reduction of waste and CO_2 footprint, energy conservation, lightening of material, and so on), it is a critical issue for building and construction department to treat the wastes properly and encourage the recycling of resources. In spite of many investigators (Chen et al., 2010; Hung & Hwang, 2007) indicate that the sintering technique has been successfully applied to recycle above-mentioned resources as lightweight aggregates. But the energy consumption and CO_2 emission of sintering process are too much to be extensively adopted. A new approach, the cold-bonding technique (Cai et al., 2010, 2012 & Tsai et al., 2011, 2012) incorporates the principles of the cement chemistry (Mehta, 1986; Mindess & Young, 1981) and composite material (Gibson, 1994), was developed to recycle these resources as recycling coarse aggregates. Consequently, the main difference between cold-bonding and sintering technique is the reduction of energy consumption and CO_2 emission.

The cold-bonding recycling coaese aggregate was regarded as a fiber reinforced concrete or a cement-based composite that is the original concept for developing cold-bonding recycling coarse aggregates. In which cement, blast-furnace slag (BF slag), and fly ash are regarded as cementitious materials or binders, the construction residual soil, granite or lime sludge is as a filler (i.e. aggregate), and the glass fiber is as a reinforcement. In view of the fundamental principle of concrete materials (Dowling, 1993; Skalny & Mindess,

1989) that is the higher packing density of component materials of concrete, the higher will be the properties of concrete. To ensure characteristics of cold-bonding recycling coarse aggregates are acceptable, the cement-based composites were granulated as the recycling coarse aggregates with a higher stress of greater than 28 MPa after proportioning and mixing. These mixture proportions and conditions of granulation will be illustrated in subsequent sections.

2. Constituent materials

The constituent materials of cold-bonding recycling coarse aggregates mainly include 1) cementitious materials: cement, BF slag, and fly ash, 2) recycling resources: the innocuous construction residual soil, granite sludge, and lime sludge, 3) other materials: the recycling glass fibers and superplasticizer.

2.1 Cementitious materials

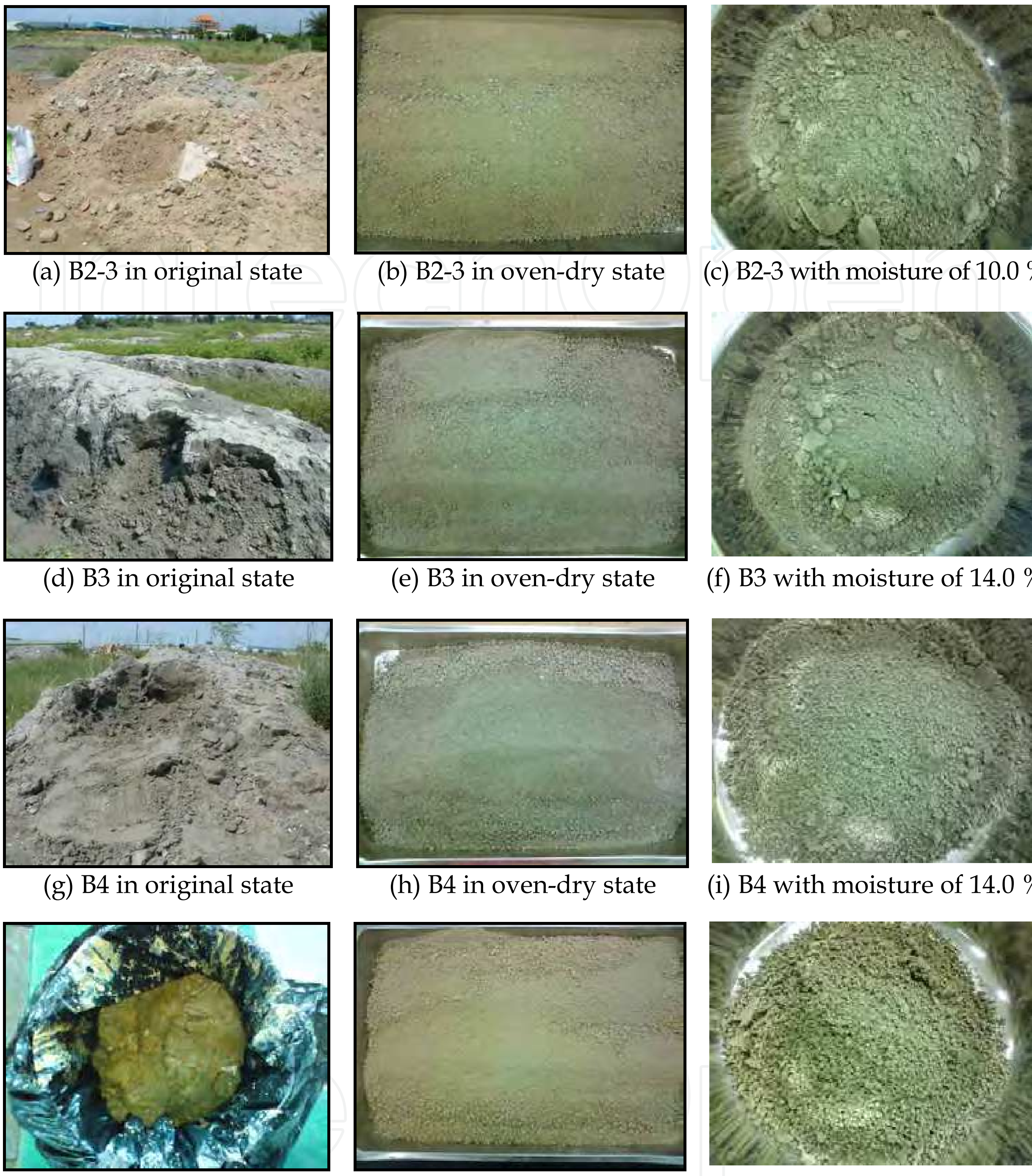
The type I Portland cement produced by Universal Cement Corporation, BF slag provided by CHC Resources Corporation, and class F fly ash supplied by Taiwan Power Station are employed to produce the cold-bonding recycling coarse aggregates. These cementitious materials conform to the related American Society for Testing and Material (ASTM) standards and their physical properties as well as chemical compositions are shown in Tables 3.

	Item	Cement	BF slag	Fly ash
Physical properties	Specific gravity	3.15	2.90	2.14
	Surface area (m^2/g)	2,970	4,350	3,110
	Time of initial setting (min)	135	-	-
	Time of final setting (min)	377	-	-
Chemical compositions (%)	SiO_2	22.16	35.56	49.86
	Al_2O_3	5.63	14.34	37.89
	Fe_2O_3	2.17	0.33	3.18
	CaO	67.35	50.23	6.04
	MgO	-	5.66	-
	SO_3	2.08	0.95	0.66
	f-CaO	0.08	-	-
	TiO_2	0.25	0.44	1.20
	Na_2O	0.31	-	-
	K_2O	0.15	0.09	0.44
	Loss on ignition	0.51	0.31	6.08

Table 3. Physical properties and chemical compositions of cementitious materials.

2.2 Recycling resources

There were four various construction residual soils (i.e. B2-3, B3, B4, and B6 categories) employed to make the cold-bonding recycling coaese aggregates as shown in Fig. 2.



(a) B2-3 in original state (b) B2-3 in oven-dry state (c) B2-3 with moisture of 10.0 %

(d) B3 in original state (e) B3 in oven-dry state (f) B3 with moisture of 14.0 %

(g) B4 in original state (h) B4 in oven-dry state (i) B4 with moisture of 14.0 %

(j) B6 in original state (k) B6 in oven-dry state (l) B6 with moisture of 14.0 %

Fig. 2. Photos of four construction residual soils in various moisture states.

In which B2-3, B3, and B4 categories were provided from a local collecting plant of construction wastes in Tainan as well as the construction residual soil of B6 category was acquired from a construction site near Shida Road in Taipei, Taiwan. For engineering purposes, these construction residual soils of B2-3, B3, B4, and B6 categories were classified as SP (i.e. poorly graded sand), ML (i.e. silt), SM (i.e. silty sand), and CL (i.e. lean clay), respectively according to Unified Soil Classification System (ASTM, 2006). Their specific gravity as well as chemical compositions are shown in Tables 4.

	Construction residual soil				Granite sludge		Lime sludge
	B2-3	B3	B4	B6	A	B	
CaO (%)	1.96	2.29	2.16	0.27	12.08	6.39	55.76
SiO_2 (%)	75.70	73.20	69.46	69.52	55.49	70.63	21.70
Al_2O_3 (%)	14.83	16.77	18.68	21.29	11.04	14.76	8.45
Fe_2O_3 (%)	3.01	3.71	4.17	4.08	10.90	2.72	2.57
MgO (%)	N.D.	N.D.	0.85	0.70	8.08	N.D.	6.07
SO_3 (%)	0.08	0.14	0.23	0.02	0.09	0.07	3.81
K_2O (%)	2.65	2.92	3.43	3.17	1.56	4.69	N.D.
TiO_2 (%)	0.54	0.67	0.72	0.70	0.22	0.29	0.39
V_2O_5 (%)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Specific gravity	2.57	2.64	2.54	2.870	2.90	2.70	2.62

Table 4. The specific gravity and chemical compositions of recycling resources.

In order to accelerate the settling of sludge for facilitating the recycling of water, the flocculants were added into the water reclamation pond in masonry plants. Therefore there were two various granite sludges (see Fig. 3), A granite sludge does not contain any flocculants and B granite sludge contains a few flocculants, were provided from the Stone and Resource Industry R&D Center in Hualien, Taiwan and their compositions were shown in Table 4.


(a) A in original state


(b) A in oven-dry state


(c) A with moisture of 19.5 %


(d) B in original state


(e) B in oven-dry state


(f) B with moisture of 20.0 %

Fig. 3. Photos of granite sludge in various moisture states.

The lime sludge (see Fig. 4) was provided from the CPDC An-Shun site that was a decommissioned chloroalkaline and pentachlorophenol manufacturing plant in Tainan, Taiwan (Chao et al., 2008). The specific gravity and chemical compositions of lime sludge are shown in Tables 4.

(a) A in original state (b) A in oven-dry state (c) A with moisture of 45.0 %

Fig. 4. Photos of lime sludge in various moisture states.

In Taiwan, the government continuously makes great efforts to promote the development of recycling materials (like green building materials, etc.) produced with the recycling wastes or resources over the past decade. For protecting the safety and health of users and purchasers, the stringent control standards were establish to prevent any noxious components from incorporating into the recycling resources. In other words, any recycling wastes or resources must confirm to the stringent control standards before they were used to manufacture any recycling products. The toxicity characteristic leaching procedure (TCLP) test acts an impotant and decisive role in the above-mentioned control standards. The TCLP results of recycling resources were below the criteria of general enterprise wastes and green building materials (Chiang, 2007) in Taiwan as shown in Table 5.

	Cr (mg/L)	Cd (mg/L)	Pb (mg/L)	Cu (mg/L)	As (mg/L)	Hg (mg/L)
B2-3 construction residual soil	<0.02	<0.02	<0.02	<0.02	0.0018	N.D.
B3 construction residual soil	<0.02	<0.02	<0.02	<0.02	N.D.	N.D.
B4 construction residual soil	<0.02	<0.02	<0.02	<0.02	N.D.	N.D.
B6 construction residual soil	<0.02	<0.02	<0.02	<0.02	0.0015	N.D.
A granite sludge	0.087	0.180	0.049	0.005	0.003	N.D.
B granite sludge	1.270	0.080	0.032	0.006	0.009	N.D.
Lime sludge	0.313	0.001	0.026	0.007	0.079	N.D.
Criteria of general enterprise wastes	5.0	1.0	5.0	15.0	5.0	0.2
Criteria of green building material	1.5	0.3	0.3	0.15	0.3	0.005

Table 5. TCLP results of recycling resources.

2.3 Other materials

Type G superplasticizer, a carboxylate-based, was purchased from local factory in Taiwan and the characteristics of superplasticizer as shown in Table 6. The glass fibers were recycled from printed circuit board (PCB) wastes by Much Fortune Technology Co., Ltd. In fact, the glass fibers also should be regarded as a recycling resource.

Item	
Specific gravity	1.09
Water reduction (%)	30.00
Solid content (%)	25.70
pH value	2.81

Table 6. The characteristics of carboxylate-based superplasticizer.

3. Mixture proportions design

This section principally introduce that a local mixture proportion method in Taiwan, densified mixture design algorithm (DMDA), is employed to design and prepare the cement-based composite for producing the cold-bonding recycling coarse aggregates, the logic and procedure of DMDA, how to design mixture proportions of cold-bonding recycling coarse aggregates by utilization of DMDA, and the mixture proportions of cold-bonding recycling coarse aggregates.

3.1 Design logic of densified mixture design algorithm, DMDA

The densified mixture design algorithm (DMDA) was developed by National Taiwan University of Science and Technology since 1992 is a mixture proportion method for cement-based composite (e.g. mortar, plain concrete, high performance, self-consolidating concrete and so on), in which the paste volume method and the current dry loose density (i.e. unit weight) method are incorporated together for obtaining the optimized cement paste through densely packing aggregates (Chang et al., 2001; Tsai, 2005; Tsai et al., 2006). The most important design logic of DMDA is the achievement of "least void" through the utilization of fly ash (to fill the void between blended aggregates) and the cement paste (to fill the rest of the void). The utilization of fly ash (in addition to the cement paste) to fill the void between blended aggregates will increase the density of cement-based composite (Tsai et al., 2006). And the addition of the super plasticizers (SP) is helpful to solve the potential problem of tangling or balling of fibers (Tsai et al., 2009, 2010). Thus the workability of the cement-based composite with the aid of SP is ensured as a result.

3.2 Design consideration of cold-bonding recycling aggregate

In conventional mixture design, the cement-based composite workability is decided by the water amount and the compressive strength whereas the durability is decided by the water-to-cement ratio (w/c) (American Concrete Institute [ACI], 1991). The workability can be improved by increasing the water amount (Neville, 2000) and the strength can be increased by increasing the cement content. However, too much cement paste will cause chemical shrinkage, and the shrinkage rate or expansion rate is in direct proportion to the water and cement amount due to the hydration of the cement (Hwang & Lu, 2000; Mather, 2000). Besides, ordinary cement-based composite contains water at least 20 % by its volume, and hence drying shrinkage will be unavoidable. So the durability of cement-based composite is destroyed due to disintegration and crack formation. To avoid these problems cement-based composite mixture designed with low water amount and low cement content is proposed.

Durability design should be considered for improving both the fresh and hardened stages of the cement-based composite and should finally extend their service life. First and foremost the cement-based composite mixture design should have a very low water amount (Neville, 2000) so as to minimize the shrinkage rate or the expansion rate (Hwang & Lu, 2000). Then, the cement-based composite must be designed to satisfy the construction needs such as with zero or low slump for cold-bonding recycling aggregate or roller compacted concrete, with high slump for self- consolidating concrete or high performance concrete, type of construction work, and the required final finished result. In plastic stage, the cement-based composite is designed to prevent the occurrence of plastic shrinkage cracks due to excess water evaporation from its surface. A certain amount of fibers should be included in the cement-based composite to absorb energy and in the case of crack formation, to stop their propagating (Rossi et al., 1987). The addition of pozzolanic materials (i.e. BF slag and fly ash) is necessary to help the self-healing of cracks if they are generated (Tsai et al., 2009). A strict standard operation procedure for mixture proportion, material selection, trial batch, quality control and curing are required to lower the possibility of crack formation.

The DMDA was adopted to design the intended cement-based composites for producing the cold-bonding recycling coarse aggregates. In order to minimize the shrinkage rate or the expansion rate and ensure the durability of cold-bonding recycling coarse aggregate, a very low water-to-cementitious ratio of 0.20 was selected to design mixture proportions of cement-based composite. And a total of 39.4 kg glass fibers (the volume=0.02 m) was added to reach the intended design value of 2.0 % by volume of the cement-based composite for preventing such cracks and enhancing the toughness as well as volume stability (Rossi et al., 1987; Tsai et al., 2009, 2010) of cold-bonding recycling coarse aggregate. In view of cement has the most energy consumption and CO_2 emission in all constituent materials of cold-bonding recycling coarse aggregate as well as the above-mentioned disadvantages, the amount of cement is limited to less than 200 kg/m^3. There were three various amount of cement (i.e. 50, 100 and 200 kg/m^3) designed for every recycling resource to magnify the application cold-bonding recycling coarse aggregates in the future.

3.3 Mixture design procedure of cold-bonding recycling aggregate by DMDA

The following steps can be used to provide computational basis for designing the cement-based composite mixture to produce the cold-bonding recycling coarse aggregates employing the DMDA procedure.

(1) Select proper material resource and gather material information.

This is an important step for the mix design of cement-based composite mixture for producing the cold-bonding recycling coarse aggregates. The basic quality information of the ingredients of cement-based composite is necessary for the purpose of quality control.

(2) Obtain the maximum dry loose density (i.e. unit weight) by iteratively packing recycling resources, BF slag, and fly ash in filler system.

(2-a) Fill fly ash with BF slag and then obtain:

$$\alpha = \frac{W_{slag1}'}{W_{slag1}' + W_{flyash}'} \tag{1}$$

where α is the ratio at maximum dry loose density as fly ash is filled with BF slag; W_{slag1}' is the weight of BF slag (kg) in filler system; W_{flyash}' is the weight of fly ash (kg).

(2-b) Fill recycling resource with the blend of fly ash and BF slag under fixed α, and obtain:

$$\beta = \frac{W_{slag1}' + W_{flyash}'}{W_{slag1}' + W_{flyash}' + W_{\mathrm{Re}}'} \tag{2}$$

where β is the ratio at maximum dry loose density as recycling resource were filled with the blend of fly ash and BF slag; W_{Re}' is the weight of recycling resource (kg).

(3) Select the volume of glass fiber (η) added into cement-based composite.

(4) Calculate the least void, V_v :

$$V_v = 1 - \sum \frac{W_i'}{\gamma_i} - \eta \tag{3}$$

where W_i' (kg/m^3) and γ_i (kg/m^3) are the weight and density of i constituent material in filler system, respectively.

(5) Assign a lubricating paste thickness (t) and calculate the volume of cement paste.

$$V_p = nV_v \tag{4}$$

where n is a multiplier for lubricating paste; V_p is the volume of cement paste.

(6) Calculate the factor of volume variation (υ) (Tsai, 2005):

$$\upsilon = \frac{1 - \eta - nV_v}{1 - \eta - V_v} \tag{5}$$

(7) Calculate the weight of recycling resource, BF slag, fly ash, and glass fiber in filler system, respectively:

$$W_{fiber} = \eta \times \gamma_{fiber} \tag{6}$$

$$W_{flyash} = \upsilon \times W_{flyash}' \tag{7}$$

$$W_{slag1} = \upsilon \times W_{slag1}' \tag{8}$$

$$W_{\mathrm{Re}} = \upsilon \times W_{\mathrm{Re}}' \tag{9}$$

where γ_{fiber} is the density of glass fiber (kg/m³); W_{fiber}, W_{flyash}, W_{slag1}, and W_{Re} are weights of glass fiber, fly ash, BF sand, and recycling resource, respectively in the cement-based composite mixture (kg/m³).

(8) Calculate the amount of cement, BF slag and mixing water in paste system:

$$V_P = n \cdot V_V = \frac{W_{water}}{\gamma_{water}} + \frac{W_{cement}}{\gamma_{cement}} + \frac{W_{slag2}}{\gamma_{slag}} \tag{10}$$

If ξ is the ratio of replacing cement with BF slag by weight, then:

$$\xi = \frac{W_{slag2}}{W_{cement} + W_{slag2}} \tag{11}$$

where W_{water}, W_{cement}, and W_{slag2} are weights of water, cement, and BF slag in paste system, respectively (kg/m³); γ_{water}, γ_{cement}, and γ_{slag} are densities of water, cement, and BF slag, respectively (kg/m³).

Substitute Equation 11 into Equation 10 to obtain:

$$V_p = \frac{\left(\frac{W_{water}}{W_{cement}}\right) W_{cement}}{\gamma_{water}} + \frac{W_{cement}}{\gamma_{cement}} + \frac{\left(\frac{\xi}{1-\xi}\right) W_{cement}}{\gamma_{slag}} \tag{12}$$

If the water-to-cementitious material ratio (w/cm) is λ, then:

$$w / cm = \lambda = \frac{W_{water}}{W_{cement} + W_{flyash} + W_{slag1} + W_{slag2}} \tag{13}$$

Using Equations 11 and 13, Equation 12 can be used to solve for W_{cement}:

$$W_{cement} = \frac{V_p - \frac{\lambda}{\gamma_w}(W_{flyash} + W_{slag1})}{[\frac{\lambda}{\gamma_{water}} + \frac{1}{\gamma_{cement}} + \frac{\xi}{1-\xi}(\frac{\lambda}{\gamma_{water}} + \frac{1}{\gamma_{slag}})]} \tag{14}$$

The calculated W_{cement} can be substituted both into Equation 11 and Equation 13 to obtain W_{slag2} and W_{water}, respectively.

(9) Determine the dosage of SP and amount of water

The dosage of SP is determined by its quality and the total water content. Under fixed total amount of water and w/cm ratio, the SP dosage can be estimated according to past experience as shown in Equation 15 and Fig. 5 (Chang et al., 2009).

$$\mathrm{SP}\ (\%) = 4.59\times10^{-5}\times X^2 - 1.81\times10^{-2}\times X + 1.98 \tag{15}$$

where X is total amount of water (kg/m³).

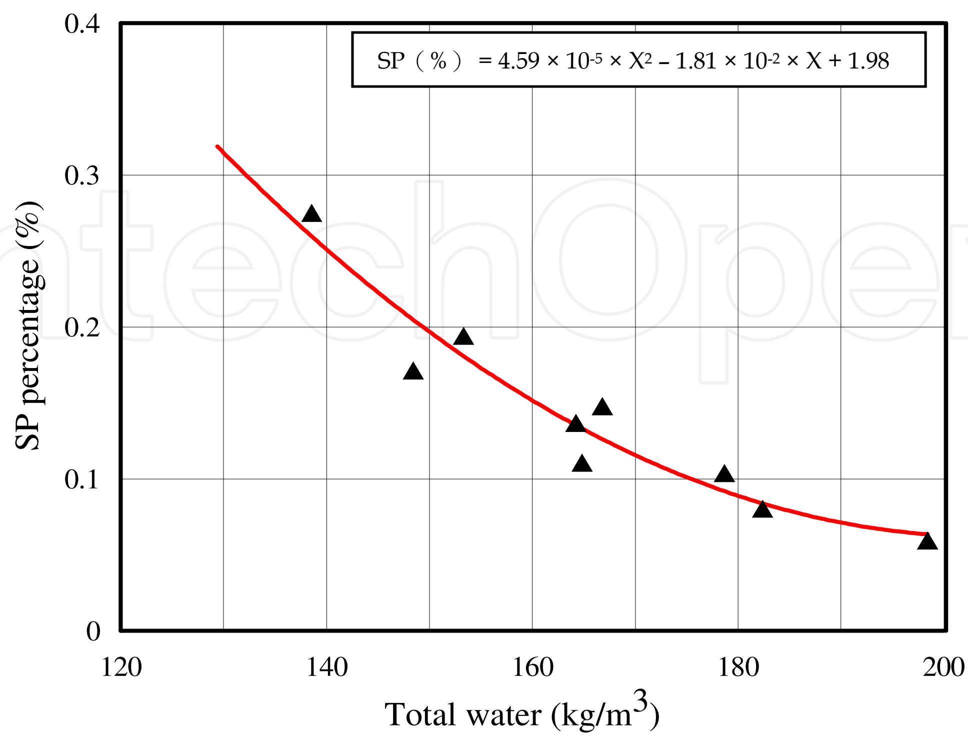


Fig. 5. The SP dosage for cold-bonding recycling coarse aggregates (Chang et al., 2009).

3.4 Mixture of cold-bonding recycling aggregate

According to the procedure of DMDA described in Section 3.3, the mixture proportions of cement-based composite with various recycling resources for producing the cold-bonding recycling coarse aggregates are shown in Table 7. For instance, B2-3-200 represents a cement-based composite contains the construction residual soil of B2-3 category and a cement amount of 200 kg/m^3; B-100 represents a cement-based composite with B granite sludge and a cement amount of 100 kg/m^3; L-50 represents a cement-based composite with lime sludge and a cement amount of 50 kg/m^3.

4. Granulation by cold-bonding technique

Dowling (1993) and Skalny & Mindess (1989) indicated that the higher packing density of component materials of cement-based composite, the higher properties of cement-based composite will be. In order to ensure that characteristics of cold-bonding recycling coarse aggregates are able to satisfy with the related criteria, a higher stress was adopted to the cement-based composites as recycling coarse aggregates. The various methods, molds, and conditions of granulation are discussed in this section.

4.1 Method of granulation

Three various methods were conducted to granulate the cement-based composites as cold-bonding recycling coarse aggregates. They are: 1) spirally push method; 2) immediately squeeze out method; 3) press ingot method. The granulation energy of spirally push method is too small to adequately form the recycling aggregates (see Fig. 6) due to the intended cement-based composite contains lower moisture to minimize the shrinkage rate or the expansion rate and ensure the durability of cold-bonding recycling coarse aggregate. On the contrary, while the cement-based composite with higher moisture could be successfully granulated by using spirally push method, but the produced recycling aggregates will not have nice properties.

Mix No.	Mixture proportions (kg/m^3)					
	Cement	BF slag	Fly ash	Recycling resource	Glass fiber	SP+Water
B2-3-50	50	150	235	1656	39.4	87
B2-3-100	100	110	255	1617	39.4	93
B2-3-200	200	20	280	1573	39.4	100
B3-50	50	150	235	1574	39.4	87
B3-100	100	110	255	1537	39.4	93
B3-200	200	20	280	1496	39.4	100
B4-50	50	150	235	1528	39.4	87
B4-100	100	110	255	1491	39.4	93
B4-200	200	20	280	1450	39.4	100
B6-50	50	150	235	1615	39.4	87
B6-100	100	110	255	1578	39.4	93
B6-200	200	20	280	1535	39.4	100
A-50	50	100	390	1403	39.4	108
A-100	100	70	345	1446	39.4	103
A-200	200	20	252	1522	39.4	95
B-50	50	100	385	1308	39.4	107
B-100	100	70	358	1324	39.4	106
B-200	200	20	252	1412	39.4	95
L-50	50	120	315	976	39.4	97
L-100	100	85	279	999	39.4	93
L-200	200	20	204	1047	39.4	85

Table 7. Mixture proportions of cold-bonding recycling aggregates.

Regardless of the cement-based composite contains how much moisture, the immediately squeeze out method will not successfully achieve the granulation of cold-bonding recycling coarse aggregate. This is due to the water within cement-based composite was drained out as shown in Fig. 7, like consolidation in geotechnical engineering (Holitz & Kovacs, 1981), during the process of granulating recycling coarse aggregates. Therefore the immediately squeeze out method also cannot be employed to form the cold-bonding recycling coarse aggregates.

(a) A commercial spirally-push machine (b) Photo of improper recycling aggregates

Fig. 6. Spirally push method.

(a) The water within cement-based composite was drained out (b) Photo of broken recycling aggregates

Fig. 7. Immediately squeeze out method.

Finally the press ingot method (see Fig. 8) was developed and successfully granulated the cold-bonding recycling coarse aggregates. Fig. 8 also shows the procedure of press ingot method and the procedure is described as follows:

Step 1: To fill the mixed cement-based composite into the mold.
Step 2: To set up the pestle into the mold.
Step 3: To press and form the recycling aggregates.
Step 4: To take off the recycling aggregates from the mold.

4.2 Optimum moisture of granulation

In the original designing concept of cement-based composites mixture proportions for producing the recycling coarse aggregates, the recycling resources were regarded as fillers (i.e aggregates of concrete). But the natures of recycling resources are quite different from primitive aggregates (e.g. particle shape, gradation, absorption, and so on). The purpose of exploring the optimum moisture of recycling resource for granulating aggregate is to avoid two issues: 1) with lower moisture: the recycling coarse aggregates can not be adequately granulated; 2) with higher moisture: the cold-bonding recycling coarse aggregates don't have only sufficient durability (Mehta, 1986; Mindess & Young, 1981; Neville, 2000) but the redundant water also will be drained out during forming recycling aggregates (like consolidation in geotechnical engineering). The drained water will result in the excessively high water-to-cement ratio (w/c) or water-to-cementitious materials (w/cm) around the surface of the recycling aggregate. And the excessively high w/c or w/cm will immensely affect the strength, hardness, abrasion resistance, soundness, permeability of the cold-bonding recycling coarse aggregate (Mehta, 1986; Mindess & Young, 1981).

(a) Step 1: To fill the mixed cement-based composite into the mold

(b) Step 2: To set up the pestle into the mold

(c) Step 3: To press and form the recycling aggregates

(d) Step 4: To take off the recycling aggregates from the mold

Fig. 8. The procedure of press ingot method.

The higher adopted stress is not always better for granulating cold-bonding recycling coarse aggregates. Because the water has the incompressible nature. While the too high stress is adopted for granulation, the water certainly will be drained out. Then the cold-bonding recycling coarse aggregate will generate cracks due to tensile stress in capillary pores caused by absorption of the drained water during unloading process. Therefore the proposed stress of granulation by using press ingot method is 35.0 to 42.0 MPa. The corresponding optimum moistures of recycling resources are shown in Table 8 and the blended cement-based composites contain the recycling resources with such moisture are shown in Fig. 2, Fig. 3, and Fig. 4. This result also implies that the cold-bonding technique is able to be applied to handle recycling resources with moisture and reduce the energy consumption and CO_2 emission resulted from the oven-dry process. It is worth mentioning that the optimum moisture of blended recycling resource can be estimated by the proportion and optimum moisture of every constituent recycling resource. For example, a blended recycling resource is composed of 40 % B2-3 construction residual soil and 60 % lime sludge, its optimum moisture will be approximate 31 %.

Type of recycling resource	Optimum moisture
B2-3 construction residual soil	10.0 %
B3 construction residual soil	14.0 %
B4 construction residual soil	14.0 %
B6 construction residual soil	14.0 %
A granite sludge	19.5 %
B granite sludge	20.0 %
Lime sludge	45.0 %

Table 8. The optimum moistures of recycling resources.

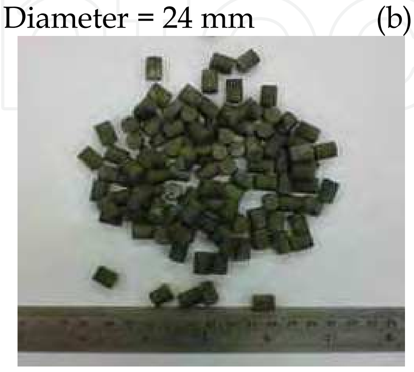
4.3 Improvement of particle shape

The press ingot method was developed and successfully granulated the cement-based composites as cylindrical cold-bonding recycling coarse aggregates with five various diamemters of 24, 18, 12, 8, and 5 mm as shown in Fig.9. Mindess & Young (1981) and Mehta (1986) indicated that aggregate shap affects the workability of fresh concrete through their influence on cement paste requirments. The ideal aggregate particle is one that is close to spherical in shape. But the spherical shape is unfavorable for mechanical properties of concrete. Whereas both of the above contentions, the cylindrical cold-bonding recycling coarse aggregates were expected to be rounder (i.e. to smooth the four corners of cylinder). Only the molds of press ingot method with three various diamemters of 24, 18, and 12 mm was improved. Because the corner effects of cylindrical cold-bonding recycling coarse aggregate with diamemter of 8 or 5 mm are very limited. After improving particle shape, the molds and recycling coarse aggregates are shown in Fig 10.


(a) Diameter = 24 mm


(b) Diameter = 18 mm


(c) Diameter = 12 mm


(d) Diameter = 8 mm

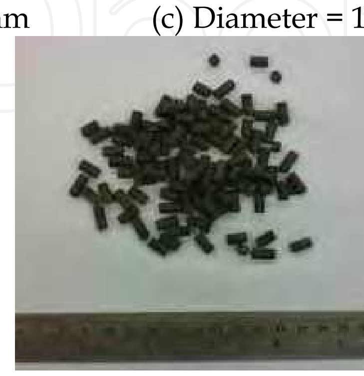
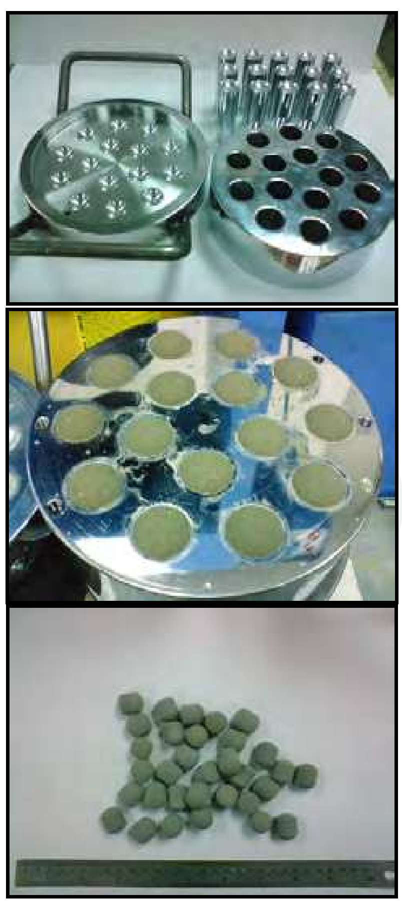

(e) Diameter = 5 mm

Fig. 9. Photos of cold-bonding recycling coarse aggregates with various diameter.


(a) Diameter = 24 mm


(b) Diameter = 18 mm


(c) Diameter = 12 mm

Fig. 10. Photos of molds and recycling aggregates after improvement of particle shape.

5. Characteristics of cold-bonding recycling coarse aggregates

The promotion of up-to-date green building materials was often impeded by the lack of relevant standards or specifications cited to verify their characteristics (Chang et al., 2009). To avoid such obstruction affecting the application of cold-bonding recycling coarse aggregates in the future, the characteristics of cold-bonding recycling coarse aggregates were certified in accordance with ASTM C33. The aggregate gradation significantly affects on workability, strength, durability, and economy of concrete (Mehta, 1986; Mindess & Young, 1981; Tsai et al., 2006). Therefore the gradation of cold-bonding recycling coarse aggregate was established by the above-mentioned five various diameter particles according to the mean of upper and lower limit from size number 56 and 6 recommended by ASTM C33.

5.1 Basic properties

After granulating cold-bonding recycling coarse aggregates by using the press ingot method, these recycling aggregates were cured in saturated limewater at the temperature of 23± 2.0 °C according to ASTM C192. They were conducted teste of basic properties include specific gravity in oven-dry (OD) and saturated surface dry (SSD) states, absorption, bulk density (i.e. unit weight) and voids according to relevant ASTM standards after the age of 28 days and these results were shown in Table 9. The result indicates that the specific gravity of

Mix No.	Basic properties				
	Specific gravity (OD)	Specific gravity (SSD)	Absorption (%)	Unit weight (kg/m^3)	Voids (%)
B2-3-50	1.80	2.07	14.9	1,191	33.9
B2-3-100	1.81	2.07	14.2	1,192	34.2
B2-3-200	1.81	2.08	14.9	1,176	35.0
B3-50	1.73	2.02	17.0	1,144	33.9
B3-100	1.73	2.01	16.4	1,153	33.4
B3-200	1.73	2.02	16.7	1,103	36.3
B4-50	1.77	2.05	15.8	1,165	34.2
B4-100	1.79	2.06	15.3	1,175	34.4
B4-200	1.80	2.08	15.5	1,141	36.6
B6-50	1.84	2.13	15.8	1,207	33.9
B6-100	1.83	2.11	15.2	1,215	33.6
B6-200	1.83	2.11	15.2	1,201	34.5
A-50	1.66	2.01	21.3	1,084	34.7
A-100	1.69	2.03	20.2	1,101	34.9
A-200	1.74	2.08	19.3	1,133	34.9
B-50	1.55	1.89	22.1	1,033	33.3
B-100	1.58	1.91	21.2	1,045	33.9
B-200	1.65	1.99	20.0	1,088	34.1
L-50	1.23	1.72	40.0	837	32.0
L-100	1.21	1.72	41.6	827	31.6
L-200	1.20	1.73	44.6	811	32.4
Standards	ASTM C127	ASTM C127	ASTM C127	ASTM C29	ASTM C29

Table 9. Basic properties of cold-bonding recycling coarse aggregates.

cold-bonding recycling coarse aggregate is lighter than primitive aggregate, and the optimum moisture of recycling resource for granulation directly influences the absorption of recycling aggregate. The more optimum moisture of recycling resource, the higher properties of cement-based composite will be.

Other characteristics of ASTM C33 (e.g. contents of chert, clay lumps and friable particles, materials less than 75 μm, and coal and lignite, abrasion, and soundness, etc.) of recycling coarse aggregate were conducted, too. The test results show that the other characteristics of recycling coarse aggregates satisfy the specification of ASTM C33 except the soundness of L-200 (see Table 10). The reason causing the soundness of L-200 is much higher than the ASTM C33 criterion of 12 % may be attributed to the fact that L-200 contains too calcium components to have adequate sulfate resistance (Mangat & Khatib, 1995). This result also implies that using lime sludge or other recycling resources with abundant calcium components to produce cold-bonding recycling coarse aggregates should choose the mixture proportions with cement amount lower than 200 kg/m^3 to ensure their sulfate resistance. Table 11 shows the comparisons of properties of cold-bonding recycling coarse aggregate between before and after improvement of particle shape. The results indicate that the unit weight, voids, and abrasion of cold-bonding recycling coarse aggregate have the significant advancement.

Mix No.	Other characteristics of ASTM C33 (%)					
	Clay lumps and friable particle	Chert (<2.4 sp gr SSD)	Materials <75μm	Coal and lignite	Abrasion	Soundness
B2-3-50	N.D.	N.D.	0.45	N.D.	45.7	8.68
B2-3-100	N.D.	N.D.	0.56	N.D.	40.7	4.93
B2-3-200	N.D.	N.D.	0.42	N.D.	35.2	1.55
B3-50	N.D.	N.D.	0.53	N.D.	48.9	11.16
B3-100	N.D.	N.D.	0.49	N.D.	44.3	8.12
B3-200	N.D.	N.D.	0.59	N.D.	39.2	4.62
B4-50	N.D.	N.D.	0.33	N.D.	46.7	11.66
B4-100	N.D.	N.D.	0.42	N.D.	42.8	8.47
B4-200	N.D.	N.D.	0.44	N.D.	38.8	4.94
B6-50	N.D.	N.D.	0.41	N.D.	43.8	8.23
B6-100	N.D.	N.D.	0.41	N.D.	40.2	4.68
B6-200	N.D.	N.D.	0.35	N.D.	34.5	1.47
L-50	N.D.	N.D.	0.53	N.D.	38.8	7.65
L-100	N.D.	N.D.	0.50	N.D.	37.4	9.87
L-200	N.D.	N.D.	0.48	N.D.	37.8	81.47
Criteria of ASTM C33	2.0 to 10.0	8.0	1.0	0.5 to 1.0	50.0	12.0

Table 10. ASTM C33 other characteristics of cold-bonding recycling coarse aggregates.

Mix No.	Before improvement of particle shape			After improvement of particle shape		
	Unit weight (kg/m^3)	Voids (%)	Abrasion (%)	Unit weight (kg/m^3)	Voids (%)	Abrasion (%)
B2-3-50	1,191	33.9	45.7	1,205	32.9	39.7
B2-3-100	1,192	34.2	40.7	1,216	33.3	35.4
B2-3-200	1,176	35.0	35.2	1,219	33.4	28.5
B3-50	1,144	33.9	48.9	1,153	33.3	44.2
B3-100	1,153	33.4	44.3	1,173	33.1	38.7
B3-200	1,103	36.3	39.2	1,182	32.9	31.7
B4-50	1,165	34.2	46.7	1,163	33.3	42.1
B4-100	1,175	34.4	42.8	1,182	32.9	36.6
B4-200	1,141	36.6	38.8	1,205	33.0	31.1
B6-50	1,207	33.9	43.8	1,215	33.4	38.2
B6-100	1,215	33.6	40.2	1,219	33.5	34.7
B6-200	1,201	34.5	34.5	1,230	32.8	27.0

Table 11. ASTM C33 other characteristics of cold-bonding recycling coarse aggregates.

5.2 Mechanical properties

Referring to ASTM C39, the cold-bonding recycling coarse aggregate was conducted single particle compressive strength test at the age of 3, 7, 10, 14, 28, 56, and 91-day, respectively. The result indicates that the higher the cement amount, the higher will be the single particle compressive strength test of cold-bonding recycling coarse aggregate as shown in Fig. 11, Fig. 12, and Fig. 13. And the single particle compressive strength increases with the increase of curing age due to the fact that the contribution of hydration of cement and pozzlanic reaction (Dinajar et al., 2008; Malhotra, 1990).

Fig. 11 shows that the cold-bonding recycling coarse aggregates using of B3 and B4 construction residual soil have worse performances. The reason may be attributed to the fact that the B3 and B4 construction wastes are belong to silt and clay with worse properties, respectively. Especially, the single particle compressive strength of recycling aggregate with B granite sludge is significantly higher than A granite sludge as shown in Fig 12. Due to B granite contains some flocculants which are helpful for cement-based composite (like the mechanism of polymer concrete). The addition of flocculants contributes the densification of capillaries and interface within cement-based composite, which will enhance the bonding strength within the recycling coarse aggregate. The cold-bonding recycling coarse aggregate using of lime sludge has the highest single particle compressive strength. The reason causing the single particle compressive strength of recycling aggregate with lime sludge higher than construction residual soil and granite sludge may be attributed to the fact that lime does not only contain a little hydration but also activate the pozzlanic reaction.

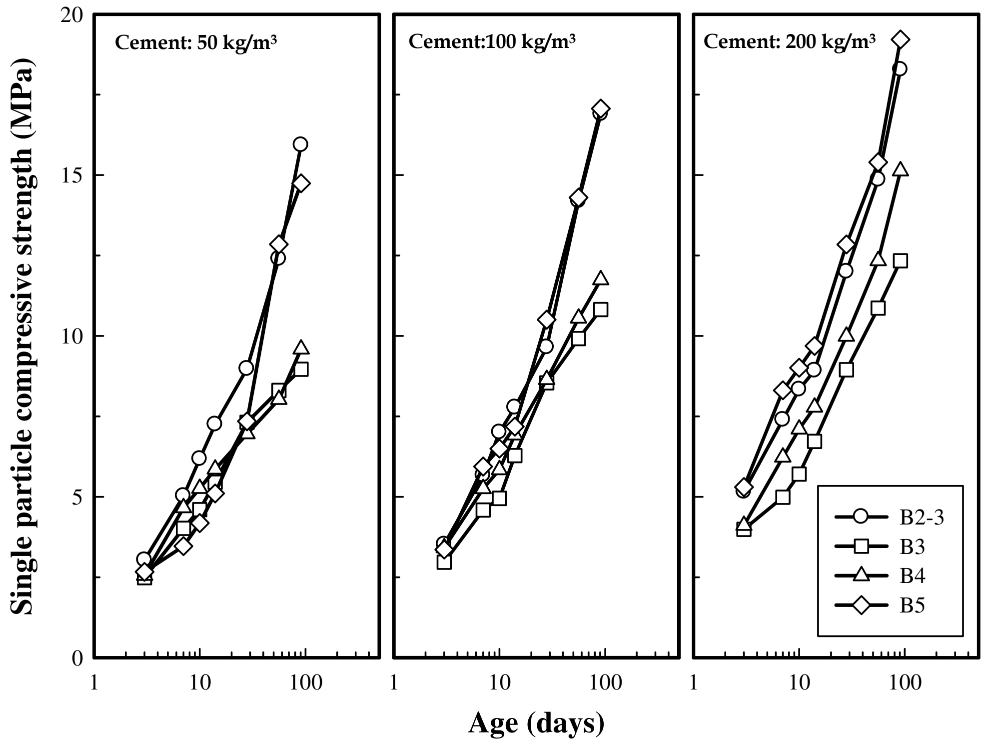


Fig. 11. The single particle compressive strength growth of recycling coarse aggregates with construction residual soil.

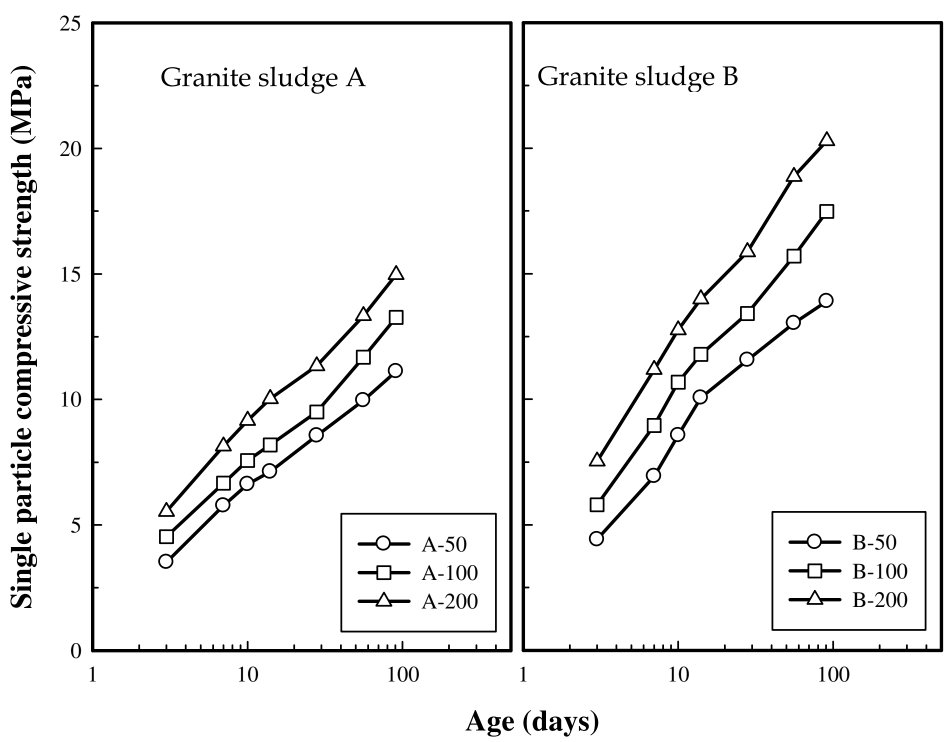


Fig. 12. The single particle compressive strength growth of recycling coarse aggregates with granite sludge.

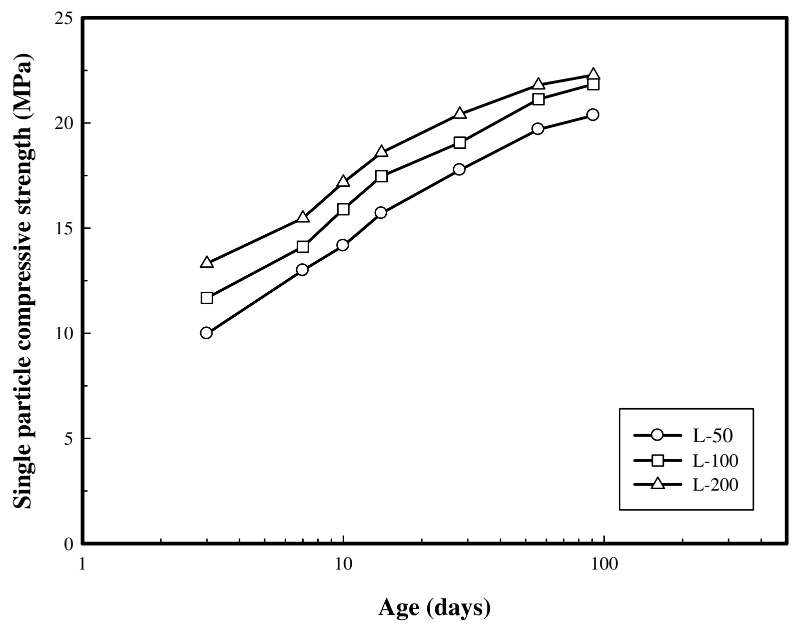


Fig. 13. The single particle compressive strength growth of recycling coarse aggregates with lime sludge.

5.3 Comparisons of various aggregates

According to an approach to estimate energy consumption, CO_2 emission, and prime cost of sintering recycling aggregates (Shiao et al., 2002), the cold-bonding recycling aggregates also was evaluated and compared with primitive and sintering aggregate. Table 6 shows the comparisons of properties, energy consumption, CO_2 emission, and prime cost of three various aggregates (primitive, sintering, and cold-bonding recycling aggregates). The results show that the recycling aggregate produced by using cold-bonding technique can reduce about 65 % CO_2 footprint than using sintering technique (Shiao et al., 2002). The prime cost of sintering recycling aggregate is 5 to 6 times higher than cold-bonding recycling aggregate. Even if the prime cost of cold-bonding recycling aggregate is lower than the primitive aggregate in Taiwan. The gradation of cold-bonding recycling aggregate is controllable and its single particle compressive strength at 91-day is 1.5 to 3 times higher than sintering recycling aggregate.

Item	Aggregate type		
	Primitive	Sintering	Cold-bonding
Gradation	Incontrollable	Single size	Controllable
Single particle compressive strength (MPa)	60.0 to 500.0	<7.0	10 to 22
Energy consumption	Low	High	Low
CO_2 emission (kg/m^3)	-	62.89	20.59
Cost (NTD/ m^3)	850	4,000	650

Table 12. Comparisons of various type aggregates.

6. Conclusion

1. The DMDA is appropriate to design the cement-based composite with recycling resources (i.e. construction residual soil, granite sludge, lime sludge) and glass fibers recycled from printed circuit board (PCB) wastes for producing the cold-bonding recycling coarse aggregates.
2. The press ingot method was developed and successfully granulated the cold-bonding recycling coarse aggregates and the procedure also was established. The proposed stress of granulation by using press ingot method is 35.0 to 42.0 MPa. The cold-bonding technique is able to be applied to handle recycling resources with moisture and reduce the energy consumption and CO_2 emission resulted from the oven-dry process. It is worth mentioning that the optimum moisture of blended recycling resource can be estimated by the proportion and optimum moisture of every constituent recycling resource.
3. The gradation of cold-bonding recycling coarse aggregate was controllable and established by the five various diameter particles according to requirements engineering or relevant standards and specifications. The unit weight, voids, and abrasion of cold-bonding recycling aggregate have the significant advancement after improvement of particle shape.
4. The recycling aggregate produced by using cold-bonding technique can reduce about 65 % CO_2 footprint than using sintering technique and the prime cost of cold-bonding recycling aggregate is 5 to 6 times lower than sintering recycling aggregate. Even if the prime cost of cold-bonding recycling aggregate is lower than the primitive aggregate in Taiwan. The single particle compressive strength at 91-day is 1.5 to 3 times higher than sintering recycling aggregate.
5. The developed cold-bonding recycling coarse aggregate could increase the reuse and recycling of wastes or recycling resources, reduce the energy consumption and CO_2 footprint, and diminish the impact on the environment and future generations. Using of lime sludge and cold-bonding technique to produce recycling coarse aggregates could not only has the above-mentioned benefits, but also these recycling aggregates would be applied to the remediation and reconstruction of CPDC An-Shun site in the future.

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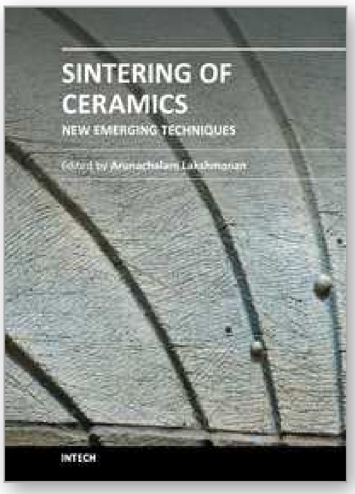

Sintering of Ceramics - New Emerging Techniques
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The chapters covered in this book include emerging new techniques on sintering. Major experts in this field contributed to this book and presented their research. Topics covered in this publication include Spark plasma sintering, Magnetic Pulsed compaction, Low Temperature Co-fired Ceramic technology for the preparation of 3-dimesinal circuits, Microwave sintering of thermistor ceramics, Synthesis of Bio-compatible ceramics, Sintering of Rare Earth Doped Bismuth Titanate Ceramics prepared by Soft Combustion, nanostructured ceramics, alternative solid-state reaction routes yielding densified bulk ceramics and nanopowders, Sintering of intermetallic superconductors such as MgB2, impurity doping in luminescence phosphors synthesized using soft techniques, etc. Other advanced sintering techniques such as radiation thermal sintering for the manufacture of thin film solid oxide fuel cells are also described.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

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