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Review

A review on the viable technology for construction waste recycling

Vivian W.Y. Tam [a,*], C.M. Tam [b,1]

[a] School of Engineering, Gold Coast Campus, Griffith University PMB50 Gold Coast Mail Centre, Qld 9726, Australia
[b] Department of Building & Construction, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong

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Abstract

Environmental problems have been considered as a serious situation in the construction. Waste management is pressing harder with the alarming signal warning the industry. Reuse, recycling and reduce the wastes consider as the only methods to recover those waste generated; however, the implementations still have much room for improvement. This paper reviews the technology on construction waste recycling and their viability. Ten material recycling practices are studied, including: (i) asphalt, (ii) brick, (iii) concrete, (iv) ferrous metal, (v) glass, (vi) masonry, (vii) non-ferrous metal, (viii) paper and cardboard, (ix) plastic and (x) timber. The viable technology of the construction material recycling should be provided an easy reference for future applications.

Keywords: Materials; Recycling; Asphalt; Brick; Concrete; Ferrous metal; Glass; Masonry; Non-ferrous metal; Paper and cardboard; Plastic; Timber; Construction

Contents

* Corresponding author. Tel.: +61 7 5552 9278; fax: +61 7 5552 8065.
E-mail addresses: v.tam@griffith.edu.au (V.W.Y. Tam), bctam@cityu.edu.hk (C.M. Tam).
1 Tel.: +852 2788 7620; fax: 852 2788 7612.

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1. Introduction

The promotion of environmental management and the mission of sustainable development have exerted the pressure demanding for the adoption of proper methods to protect the environment across all industries including construction. Construction by nature is not an environmental-friendly activity. The hierarchy of disposal options, which categorizes environmental impacts into six levels, from low to high; namely, reduce, reuse, recycle, compost, incinerate and landfill (Peng et al., 1997) (see Fig. 1). Three main waste minimization strategies of reuse, recycle and reduction, are collectively called the "3Rs". To reduce construction waste generated on site, coordination among all those involved in the design and construction process is essential.

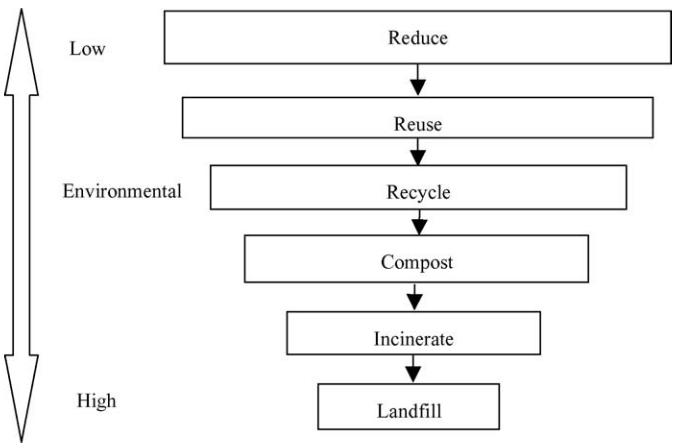

Fig. 1. Hierarchy of construction and demolition waste (Peng et al., 1997).

Recycling, being one of the strategies in minimization of waste, offers three benefits (Edwards, 1999): (i) reduce the demand upon new resources, (ii) cut down on transport and production energy costs and (iii) use waste which would otherwise be lost to landfill sites. Construction and demolition (C&D) wastes including demolished concrete (foundations, slabs, columns, floors, etc.), bricks and masonry, wood and other materials such as dry wall, glass, insulation, roofing, wire, pipe, rock and soil (Coventry, 1999) constitute a significant component of the total waste.

In order to improve the existing practices of waste recycling, this paper focuses on the following objectives:

(i) investigating the waste management in the construction;
(ii) examining the importance on materials recycling;
(iii) reviewing the viable technology for ten construction waste recycling: (i) asphalt, (ii) brick, (iii) concrete, (iv) ferrous metal, (v) glass, (vi) masonry, (vii) non-ferrous metal, (viii) paper and cardboard, (ix) plastic and (x) timber.

2. Construction waste problem

Waste is defined as any material by-product of human and industrial activity that has no residual value (Serpell and Alarcon, 1998). From the statistic of EPD (2005) (Table 1), 38% of the wastes are generated from C&D activities, which is around 6408 tonnes of wastes per annum are produced from construction activities. In 2001, the quantities of the ferrous metals represented at 45.5% with 803,190 tonnes of the total recyclable materials and 37.7% with 665,539 tonnes from wood and paper. Non-ferrous metals have the higher values of recyclable volume, in which it valued as 1000 million (Table 2). For the total recyclable materials, ferrous metals, non-ferrous metals, wood and paper are incorporated to around 87% of the total quantity of exported recyclable materials and of the total values of the materials. Therefore, it is necessary to reduce the waste generated of those three categories of materials for effectively and efficiently reduce the problem in wastage.

A comprehensive construction waste management is urgently needed on every construction site. After identifying the causes of construction waste, it is of great importance to structure ways to minimize it as the most favorable solution to waste problem of any kind. Indeed, it should be made compulsory that every construction company should enact construction waste management plan tailored to its particular mode of business so that every personnel from the management to the operational level can head for the same goal of construction waste management. Besides reduction strategies, economic issues in construction waste management in terms of recycling and contractual implications also play a significant role.

3. Construction waste recycling

Table 3 shows the recovery rates of several types of materials, such as paper, plastic, metals and glass, in Hong Kong, Australia, Japan, USA, Germany and United Kingdom.

Table 1
Quantities of solid waste disposed of at landfills in 2001 (EPD, 2002)

Waste type	Quantity (tpd)		
	Public	Private	Total
(a) Domestic waste			
Waste from household, public cleansing	5822	1644	7466
Bulky waste	28	57	85
Sub-total	5850	1701	7551
(b) Commercial waste			
Mixed waste from commercial activities	–	1120	1120
Bulky waste	–	68	68
Sub-total		1187	1187
(c) Industrial waste			
Mixed waste from industrial activities	–	534	534
Bulky waste	–	28	28
Sub-total		562	562
(d) Municipal solid waste received at disposal facilities (a + b + c)	5850	3450	9300 (55%)
(e) Construction and demolition waste (landfilled)	–	6408	6408 (38%)
(f) Special waste (landfilled)	502	607	1109 (7%)
(g) All waste received at landfills (d + e + f)	6352	10465	16817

Notes: Public waste collectors are waste collected by Food and Environmental Hygiene Department contractors and other government vehicles. Publicly collected domestic waste included some commercial and industrial waste. Special waste included abattoir waste, animal carcasses, asbestos, clinical waste, condemned goods, livestock waste, sewage treatment and waterworks treatment sludge, sewage works screenings and stabilized residues from Chemical Waste Treatment Centre.

Germany clearly has the highest recovery rates when compared with other countries; 169, 108, 105 and 88% of recovery rates for paper, plastic, metals and glass, respectively.

Hong Kong recycling practices is lagging behind in comparison with other countries. Much of the construction wastes go to landfill. There are many opportunities for the industry to act to minimize this (CIRIA, 1993) in order to prolong the life of landfill sites, minimize transport needs and reduce the primary resource requirements (mineral and energy).

4. Viable technology on construction waste recycling

Although there are many material recycling schemes recommended, actual administering of C&D waste recycling is limited to a few types of solid wastes. When considering a recyclable material, three major areas need to be taken into account (Mindess et al., 2003): (i) economy, (ii) compatibility with other materials and (iii) material properties. From a purely economic point of view, recycling of C&D waste is only attractive when the recycled product is competitive with natural resources in relation to cost and quantity. Recycled materials will be more competitive in regions where a shortage of both raw materials and landfilling sites exists.

It investigates the technology on construction waste recycling and their viability. Ten material recycling practices are studied, including: (i) asphalt, (ii) brick, (iii) concrete, (iv)

Table 2
Quantities and values of exported recyclable materials by type (EPD, 2002)

Category of recyclable materials	Quantity (tonnes)	Value (HK$ thousand)	Value per unit weight (HK$/tonnes)
Ferrous metals			
Alloy steel scrap	16471	72171	4382
Pig or cast iron	42970	46667	1086
Tinplate	572	1134	1983
Other scraps	743177	606669	816
Sub-total	803190 (45.5%)	726641 (27.9%)	905
Non-ferrous metals			
Aluminum	17044	69285	4065
Copper and alloys	47580	296645	6235
Lead	2785	4424	1589
Metal ash and residues	226	13144	58159
Nickel	63	1273	20206
Precious metal	117	656386	5610137
Tin	2	39	19500
Zinc	1270	11251	8859
Sub-total	69087 (3.9%)	1052447 (40.4%)	15234
Plastics			
Polyethylene	115653	124594	1077
Polystyrene and copolymers	18445	48076	2606
Polyvinyl chloride	2234	5065	2267
Others	71401	120381	1686
Sub-total	207733 (11.8%)	298116 (11.4%)	1435
Textiles			
Cotton	16539	25746	1557
Man-made fibres	57	295	5175
Old clothing and other textile articles, rags, etc.	3434	11700	3407
Sub-total	20030 (1.1%)	37741 (1.4%)	1884
Wood and paper			
Paper	657336	487785	742
Wood (include sawdust)	8203	4274	521
Sub-total	665539 (37.7%)	492059 (18.9%)	739

ferrous metal, (v) glass, (vi) masonry, (vii) non-ferrous metal, (viii) paper and cardboard, (ix) plastic and (x) timber.

4.1. Asphalt

In the Netherlands, 50% asphalt waste was used for the production of new asphalt, containing 10–15% recycled asphalt added to new asphalt in 1990 (Hendriks and Pietersen, 2000). The remaining broken asphalt can be bonded with cement and used in place of sand or cement sub-bases. Old asphalt materials are crushed for recycling as asphalt aggregate, mixed with sand and binder. The binder can be either cement or a liquid in the form of a bituminous emulsion; a combination of cement and a liquid binder are used as well. In

Table 3
Recovery rates of common recyclable materials (EPD, 2005)

Place	Year	Paper (%)	Plastic (%)	Metals (%)	Glass (%)
Hong Kong	2001	58	38	89	3
Australia	1995	51	30 (polyethylene terephthalate (PET) bottles); 42 (high-density polyethylene (HDPE) bottles)	65 (aluminium (Al) can); 23 (others)	42
Japan	2000	58	14	75	78 (glass bottles)
USA	1999	42	6	35	23
Germany	1999	169[a]	108	105 (finplate); 87 (Al can)	88
United Kingdom	1998	38	3	43 (Al can); 35 (ferrous scrap)	22

[a] Percentages greater than 100% mean materials being recycled for more than one time.

addition to these binders, asphalt aggregate can also be stabilized with blast furnace slag or fine slag. Only a limited proportion of asphalt can be reused in highly pervious road surface, as the composition of these mixtures is highly critical.

Several recycling technologies had been implementing in recycling asphalt materials (Hendriks and Pietersen, 2000): (i) *cold recycling*, water and stabilizing agent, such as cement, foamed bitumen and emulsified bitumen are added (Cheung, 2003); (ii) *heat generation* results in a rearrangement of the original physical properties and chemical compositions of the bitumen; (iii) *Minnesota process* is heated the old asphalt at above normal temperature (180 °C) for heat transfer to restructure the old materials; (iv) *parallel drum* process is undertaking preheating in a separate dryer and heater drum; (v) *elongated drum* process includes drying and heating of the aggregate, adding asphalt aggregate, followed by adding filler and bitumen, and finally, mixing of all components; (vi) *microwave asphalt recycling system* includes de-ironing and crushing the asphalt rubble; (vii) *Finfalt* process can produce the recycled asphalt immediately prior to dosage by a mobile plant treating the materials; (viii) *surface regeneration* refers to all techniques where asphalt in the road is heated to a depth of several centimetres below the surface and is subsequently processed again in situ.

4.2. Brick

Bricks arising from demolition may be contaminated with mortar, rendering and plaster, and are often mixed with other materials such as timber and concrete. Separation of the potentially valuable facing bricks will be usually difficult and require hand sorting. In Denmark, only 10–15% bricks from old buildings are facing bricks (Kristensen, 1994), thus the sorting and cleaning of bricks tend to be more labour-intensive and costly. Any significant contamination of the bricks will render their uses uneconomically, as clean-up costs far outweigh the cost of natural brick. In the practices of a construction site in Kyoto, Japan in 2004, it burns the demolished bricks into slime burnt ash. And, in recent year, bricks are commonly be crushed to form filling materials and hardcore in Hong Kong.

Table 4
Reuse of demolished concrete (Kawano, 1995)

Demolished member	Man-made reef, paving stone
Broken into 200–400 mm	Protection of levee
Crushed (−50 mm)	Sub-base, backfilling, foundation materials
Crushed and worn (−40 mm)	Concrete and asphalt concrete aggregate sub-base material, backfilling material
Powder (by-product through crushing)	Filler for asphalt concrete, soil stabilization materials

4.3. Concrete

The most usual way to recycle concrete rubble is categorized as bound (natural aggregate replacement in new concrete) and unbound (road base, trench, etc.). Although unbound use is consuming most of the volumes of more than 90%, recent papers have documented acceptable concrete qualities with aggregate replacement up to 30% in new concrete (Coventry, 1999; Hendriks and Pietersen, 2000; Masters, 2001). Table 4 shows the examples of reusable concrete waste (Kawano, 1995).

4.4. Ferrous metal

There is a highly developed market for ferrous metal recycling all over the world. It is by far the most profitable and recyclable material. The demands for ferrous metal have long been well established; therefore, the applications of material had been well accepted on site.

Preferably, steel should be reused directly. If it is unsuitable for direct reuse, it is melted to produce new steel. In the Netherlands, more than 80% scrap arising is recycled, while almost 100% may be claimed to be recyclable. Steel organization reports that roughly 100% steel reinforcement is made from recycled scrap and 25% steel sections are made from recycled scrap. Scrap steel is almost totally recycled and allowed repeated recycling (Coventry, 1999). In Japan, steel used for construction including steel form and rebar is fabricated or cut to size off-site with the cutting waste, 100% steel can be recycled to avoid wastage at construction site.

4.5. Glass

In 1997, the glass industry recycled 425,000 tonnes of glass in the United Kingdom (Coventry, 1999). However, the recycling rate is relatively low in Hong Kong (1%) in comparison with other countries (the rates in USA, Japan and Germany are 20, 78 and 85%, respectively). Glass can be reused in the construction industry for a number of applications:

(i) Window: if care is taken during the demolition phase, glass window unit can be reusing directly (Coventry, 1999); depending on how carefully they are handled, stored, transported and contaminated.
(ii) Glass fibre: for material properties enhancement, glass is recycled in the manufacture of glass fibre, which is used in thermal and acoustic insulations, which can be mixed with strengthen cement, gypsum or resin products (Coventry, 1999). Japan practices

adopted recycled glass as isolation material, including glass wool mat; pipe cover and thermal insulation board with facing for plant; ceiling board and acoustical insulation board for industrial and commercial building; glass wool board and glass wool blanket without binder for automobile.

(iii) Filling material: United Kingdom practices recycled glass as a fine material for cement replacement called "ConGlassCrete", which is used for improving the strength of concrete.

(iv) Tile: 100% replacement of recycled glass adopted in the United States. It has an attractive reflective appearance on the surface after polishing.

(v) Paving block: it is produced from recycled glass aggregate by crushing in USA. Hong Kong is also developing this recycling technology, which can (i) provide an attractive reflective appearance on the surface after polishing; (ii) reduce water absorption of concrete block; (iii) provide good compressive strength. However, the problems on instability, sharpness of aggregate and alkali-silica reaction expansion need to be resolved. By adopting pulverized fly ash for depressant in alkali-silica reaction and reduce the impurities are necessary in improving the quality of paving block adopting recycled glass aggregate.

(vi) Asphalt in road: old glass is required to crush into very fine material in replacing asphalt. Taiwan practices replaced 15% recycled glass for asphalt used.

(vii) Aggregate in road: crushed glass has been developed for use as an aggregate in bituminous concrete pavement; popularly known as 'glassphalt' and it had been tested in USA (Coventry, 1999).

(viii) Aggregate in concrete: a novel fine aggregate consisting mainly of glass has been developed for use as concrete in Sweden. The presence of glass in secondary aggregate used for concrete or asphalt production may reduce the strength of the resulting material (Hendriks and Pietersen, 2000). 'Microfiller' is the result of an industrial process consisting of steps for the purification of the glass material by separation and washing. The glass is then dried, crushed and ground to the required specification and the particle size grading is defined between the size grading of cement and aggregate. The product is added to the concrete batch in the mixing process along with other constituents, and acted as a pozzolanic material. The addition of the Microfiller will improve the concrete properties in the fresh as well as in the hardened state.

(ix) Man-made soil: Japan practices adopted waste glass as ultra-fine particles at high temperature.

4.6. Masonry

Masonry is normally crushed as recycled masonry aggregate. A special application of recycled masonry aggregate use it as thermal insulating concrete containing polystyrene beads (Hendriks and Pietersen, 2000), which provides a lightweight type of concrete and with high thermal insulation. Another potential application for recycled masonry aggregate is to use it as aggregate in traditional clay bricks as well as in sodium silicate brick (Hendriks and Pietersen, 2000):

(i) A little portion of recycled masonry aggregate is used as a replacement for clay in brick and as a sand replacement in sodium silicate brick.
(ii) For use in traditional clay brick, this fraction should not contain any lime to prevent adverse effects on strength, shrinkage, durability and colour.
(iii) When used in sodium silicate brick, this fraction may contain lime; but the sodium silicate brick should be produced at a pressure of 15 bar and at lower temperatures than clay brick.

When the recycled masonry aggregate is used for sodium silicate brick, adhering cement has to be removed by a mechanical or thermal process. Interfacial stress is created when cement covered brick is heated to 900 °C and the cement can then be removed as fines (Hendriks and Pietersen, 2000). This material can be heated to produce clinker. The volume of carbon dioxide (CO_2) produced by this process is lower than that when natural material is used. Lime mortar can be reused after heating; but the adhesive has to be removed mechanically when processing sodium silicate brick.

4.7. Non-ferrous metal

The main non-ferrous metal collected from C&D sites are aluminum, copper, lead and zinc (Coventry, 1999). Once sorted, products can be sold to scrap metal merchants for recycling or directly to end-users by melting. In United Kingdom, aluminum usage is up to 95,000 tonnes with about 70% recycled in 1997; copper is recycled up to 119,000 tonnes out of a national market of 262,000 tonnes used (100% recycling rate can be achieved); lead is recycled up to 228,700 tonnes (about 85% lead used is recyclable); zinc is recycled nearly 60,000 tonnes in the production of galvanized steel strip and 40,000 tonnes in the production of protecting steel galvanized after fabrication. Relatively small quantity of zinc sheet (2000 tonnes per year) is used for roofing cladding and to some extent flashing. Furthermore, a large quantity of zinc (representing 30% of the composition) is used in the production of brass (Coventry, 1999).

4.8. Paper and cardboard

Paper and paperboard comprise approximately 37% C&D wastes by volume (EPD, 2002). It usually attracts recyclers to reprocess them as new paper product by purification (Hendriks and Pietersen, 2000). Furthermore, in recent years, the material suppliers are recommended to reuse their original packaging materials.

4.9. Plastic

High level reuses of polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinylchloride (PVC) are possible for recycling if these materials are collected separately and clean (Hendriks and Pietersen, 2000). Recycling is difficult if plastic wastes are mixed with other plastics or contaminants. The scope for high level recycling is limited due to the deterioration in properties of old plastic. Virgin material has to be added for recycling. In the Netherlands, the recycling material is used for the production of new plastic profiles containing 70% recycled material; 30% virgin material is used for ensuring sufficient UV-resistance (Hendriks and Pietersen, 2000). In future, it may be possible to improve this replacement ratio up to 80 or 90%.

There are several principal opportunities to address when considering the recycling of plastic (Coventry, 1999):

(i) Panel: the recycling of transparent PVC roofing panel started in 1992. Due to contamination and the reinforcement, the recycling material has a poorer quality than new roofing element, and therefore they can only be used for the lower face. The panel is converted to powder by cryogenic milling. The powder is then mixed with plasticizers and other materials for the production of new panel (Hendriks and Pietersen, 2000).
(ii) Plastic may be recycled and used in products specifically designed for the utilization of recycled plastic, such as street furniture, roof and floor, piling, PVC window, noise barrier, cable ducting and pipe, panel, cladding and insulation foam.
(iii) Technology is being developed that will enable building materials to be progressively infused with recycled plastic constituent in order to increase strength, durability and impact resistance, and enhance appearance. This has resulted in companies creating versatile product for plastic lumber and aggregate in asphaltic concrete.
(iv) Plastic may be utilized for further construction application. Due to volume, time and financial constraint, the recycling of plastic component is limited to landfill drainage and asphalt (Sustainable Construction, 1994).
(v) Man-made soil: Japan practices adopted after burning wasted plastic at high temperature and turning them into ultra-fine particles.

4.10. Timber

Timber waste from C&D works is produced in large quantity all over the world. It is estimated that more than 2.5 million tonnes of timber wastes generated in the United Kingdom each year (Coventry, 1999; Masters, 2001). Timber waste has a potential of being recycled as:

(i) Whole timber arising from C&D activities can be utilized easily and directly for reused in other construction projects after cleaning, de-nailing and sizing. Undamaged wood can be reused as plank, beam, door, floorboard, rafter, panel, balcony parapet and pile (Hendriks and Pietersen, 2000). In 2004, Japan developed a new technology in turning timber waste into furniture, shoring wooden pile for relocated pine trees, wood bench and timber stair.
(ii) A special lightweight concrete can be produced from aggregate made from recycled small wood chunk.
(iii) Timber waste can be recycled as energy, such as fuel, charcoal for power generation in Japan. In the Netherlands, 400,000 tonnes of wood from C&D activities are generated (Hendriks and Pietersen, 2000); most of this wood is landfilled or incinerated as a by-product in either coal-fired power plant or cement kiln; prior to incineration the wood will have be reduced in size drastically. Blast furnace deoxidization is also adopted in recycling timber.

Table 5
Summary on the experiences on technology of material recycling practices

C&D materials	Recycling technology	Recycled product
Asphalt	Cold recycling Heat generation Minnesota process Parallel drum process Elongated drum Microwave asphalt recycling system Finfalt Surface regeneration	Recycled asphalt Asphalt aggregate
Brick	Burn to ash Crush into aggregate	Slime burnt ash Filling material Hardcore
Concrete	Crush into aggregate	Recycled aggregate Cement replacement (replace the cement by the fine portion of demolished concrete) Protection of levee Backfilling Filler
Ferrous metal	Melt Reuse directly	Recycled steel scrap
Glass	Reuse directly Grind to powder Polishing Crush into aggregate Burn to ash	Recycled window unit Glass fibre Filling material Tile Paving block Asphalt Recycled aggregate Cement replacement Man-made soil
Masonry	Crush into aggregate Heat to 900 °C to ash	Thermal insulating concrete Traditional clay brick Sodium silicate brick
Non-ferrous metal	Melt	Recycled metal
Paper and cardboard	Purification	Recycled paper
Plastic	Convert to powder by cryogenic milling Clipping Crush into aggregate Burn to ash	Panel Recycled plastic Plastic lumber Recycled aggregate Landfill drainage Asphalt Man-made soil
Timber	Reuse directly Cut into aggregate Blast furnace deoxidization Gasification or pyrolysis Chipping Molding by pressurizing timber chip under steam and water	Whole timber Furniture and kitchen utensils Lightweight recycled aggregate Source of energy Chemical production Wood-based panel Plastic lumber Geofibre Insulation board

(iv) After hydrolysis by gasification or pyrolysis in incinerating or decomposing the wasted wood, timber can be recycled as chemical product (Hendriks and Pietersen, 2000).
(v) Timber fragment arising from C&D work can be recycled and utilized in new construction products in the production of wood-based panel for roof, ceiling and floor, cladding in agricultural building, hoarding, a packaging substitute, wall and sound barrier.
(vi) Paper, recycled board and mulching material are adopted by recycling timber in Japan. Furthermore, wasted timber in the form of woodchip can also be mixed with topsoil to improve soil texture and coated with plastic to form a product called plastic lumber.
(vii) Clipped timber is recycled by spraying them onto sloped soil surface in Japan, which is called "geofibre".
(viii) Timber waste can be recycled to produce insulation board, kitchen utensil and furniture from the chipped timber by pressurization at around 180 °C for 40 min with steam, water and addition of binder. In 2004, Japan practices adopted this technology in turning timber chip into paving material.

5. Conclusion

As environmental protection had been pressing hardly in all over the world, the pollution generation from construction activities seems difficult to control. The most effective way to reduce the waste problem in construction is agreed in implementing reuse, recycling and reduce the construction materials in construction activities. This paper reviews the technology on construction waste recycling and their viability. Ten material recycling practices are studied, including: (i) asphalt, (ii) brick, (iii) concrete, (iv) ferrous metal, (v) glass, (vi) masonry, (vii) non-ferrous metal, (viii) paper and cardboard, (ix) plastic and (x) timber. The recycling technology of these 10 typical C&D wastes is investigated and summarized in Table 5. Different recycled materials can be produced. The most common recycled material produced is recycled aggregate for lower-grade applications; some other higher-grade applications are also encouraged, for examples, produced as competitive as new materials. The development of viable technology for various construction materials is invaluable for the construction industry.

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