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Review

Utilization of solid wastes in construction materials

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The main objective of this study is to investigate the potential use of various solid wastes for producing construction materials. The paper is based on the comprehensive review of available literature on the construction materials including different kinds of solid wastes. The traditional methods for producing construction materials are using the valuable natural resources. Besides, the industrial and urban management systems are generating solid wastes, and most often dumping them in open fields. These activities pose serious detrimental effects on the environment. To safeguard the environment, many efforts are being made for the recycling of different types of solid wastes with a view to utilizing them in the production of various construction materials. This paper discusses the environmental implications caused by the generation of various solid wastes, and highlights their recycling potentials and possible use for producing construction materials. In addition, this paper shows the applications of solid waste based construction materials in real construction, and identifies the research needs.

Key words: Construction, construction materials, environment, recycling, solid wastes.

INTRODUCTION

The traditional construction materials such as concrete, bricks, hollow blocks, solid blocks, pavement blocks and tiles are being produced from the existing natural resources. This is damaging the environment due to continuous exploration and depletion of natural resources. Moreover, various toxic substances such as high concentration of carbon monoxide, oxides of sulfur, oxides of nitrogen, and suspended particulate matters are invariably emitted to the atmosphere during the manufacturing process of construction materials. The emission of toxic matters contaminates air, water, soil, flora, fauna and aquatic life, and thus influences human health as well as their living standard. Therefore, the issues related to environmental conservation have gained great importance in our society in recent years (Xue et al., 2009). The decision-makers in political, economic, and social sectors are now seriously offering more attention to the environment issues. Consequently, major changes regarding the conservation of resources and recycling of wastes by proper management are taking place in our ways of living and working. Many authorities and investigators are lately working to have the privilege of reusing the wastes in environmentally and economically sustainable ways (Aubert et al., 2006). The utilization of solid wastes in construction materials is one of such innovative efforts.

The cost of construction materials is increasing day by day because of high demand, scarcity of raw materials, and high price of energy. From the standpoint of energy saving and conservation of natural resources, the use of alternative constituents in construction materials is now a global concern. For this, the extensive research and development works towards exploring new ingredients are required for producing sustainable and environment-friendly construction materials. The present study investigates the potential use of various solid wastes in the production of construction materials. Besides, this

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Table 1. Different types and sources of solid wastes and their recycling and utilization potentials for construction materials (adapted from Pappu et al., 2007).

S/No.	Type of solid wastes	Source details	Recycling and utilization potentials
1	Agro-waste (organic)	Baggage, rice and wheat straw and husk, saw mill waste, ground nut shell, jute, sisal, cotton stalk, vegetable residues	Cement boards, particle boards, insulation boards, wall panels, roof sheets, binder, fibrous building panels, bricks, acid-proof cement, coir fiber, reinforced composites, polymer composites
2	Industrial waste (inorganic)	Coal combustion residues, steel slag, bauxite red mud, construction debris	Bricks, blocks, tiles, cement, paint, fine and coarse aggregates, concrete, wood substitute products, ceramic products
3	Mining/mineral waste	Coal washeries waste; mining waste tailing from iron, copper, zinc, gold and aluminium industries	Bricks, fine and coarse lightweight aggregates, tiles
4	Non hazardous waste	Waste gypsum, lime sludge, lime stone waste, broken glass and ceramics, marble processing residues, kiln dust	Blocks, bricks, cement clinker, hydraulic binder, fibrous gypsum boards, gypsum plaster, super-sulfated cement
5	Hazardous waste	Contaminated blasting materials, galvanizing waste, metallurgical residues, sludge from waste water and waste treatment plants, tannery waste	Boards, bricks, cement, ceramics, tiles

study gives several examples on the use of solid waste based construction materials in real construction.

MAJOR SOLID WASTES AND THEIR POTENTIAL USE IN CONSTRUCTION MATERIALS

Growth of population, increasing urbanization, and rising standards of living due to technological innovations have contributed to increase the quantity of a variety of solid wastes generated by industrial, mining, domestic and agricultural activities. Different types and sources of solid wastes are shown in Table 1. Globally, the estimated quantity of solid wastes generation was 12 billion tons in the year 2002 (Pappu et al., 2007). Among this amount, 11 billion tons were industrial solid wastes and 1.6 billion tons were municipal solid wastes. About 19 billion tons of solid wastes are expected to be generated annually by the year 2025 (Yoshizawa et al., 2004). Annually, Asia alone generates 4.4 billion tons of solid wastes. About 6% of this amount is generated in India (Yoshizawa et al., 2004; CPCB, 2000). Malaysia is expected to exceed 15,000 tons of solid wastes generation daily. The major solid wastes are generated in Malaysia from agricultural, industrial, municipal and mining sources. The disposal of these wastes has become a major environmental problem in Malaysia and thus the possibility of recycling the solid wastes for use in construction materials is of increasing importance.

The recycling of solid wastes in civil engineering applications has undergone considerable development over a very long time. The utilization of fly ash, blast furnace slag, phosphogypsum, recycled aggregates, red mud, Kraft pulp production residue, waste tea, etc., in construction materials shows some examples of the success of research in this area. Similarly, the recycling of hazardous wastes for use in construction materials and the environmental impact of such practices have been studied for many years (Cyr et al., 2004). The recycling and utilization potentials of different kinds of solid waste are shown in Table 1. In fact, there is a great scope for setting up secondary industries for the recycling and use of huge solid wastes in construction materials, as can be understood from Table 1. The uses of different types of solid waste in construction materials are shown in Table 2.

Fly ash and bottom ash

Fly ash (FA) and bottom ash (BA) are produced as a

Table 2. Major solid wastes and their uses in the production of construction materials.

S/No.	Name of waste	Type of waste	Use in construction materials
1	Fly ash, bottom ash, rice husk ash, palm oil fuel ash, organic fibers	Agro-industrial	Aggregate, concrete, supplementary cementing materials, blended cement, bricks, tiles, blocks, particle boards, insulation boards, cement boards, wall panels, roof sheets, reinforced polymer composites
2	Phosphogypsum, waste glass, granulated blast-furnace slag, waste steel slag, rubber tire	Industrial	Fine and coarse aggregates, blended cement, concrete, bricks, blocks, tiles, ceramic products
3	Quarry dust	Mining/mineral	Fine and coarse aggregates, concrete, bricks, tiles, blocks, surface finishing materials
4	Construction and demolition debris (concrete rubble, tiles, waste bricks, etc.)	Industrial	Fine and coarse aggregates, concrete, bricks, blocks, sub-base pavement materials

by-product from municipal solid waste incinerators and coal fuelled power stations. FA is a highly dispersible powder. It contains mainly aluminosilicate and ferriferrous glassy spherical particles (about 60 - 80%) and irregularly shaped grains of amorphous clay, mullite quartz and unburned metamorphic fuel (Malhotra and Ramezaniarpour, 1994; Diamond, 1986). BA consists of irregular particles, which can be up to 10-15 mm in size. The chemical compositions of FA and BA ashes from the same power plant are similar (Yun et al., 2004). Depending on the cooling conditions, the glassy or crystalline phase can be predominating in BA (Nisnevich et al., 2001). As a rule, BA is inert and can be used as aggregate for producing construction materials such as mortar and concrete. In addition, BA can be used directly as aggregate in road construction (Bruder-Hubscher et al., 2001).

Fly ash obtained from coal combustion is frequently used in concrete as a cost-effective substitute for portland cement. The pozzolanic properties of fly ash improve the strength of concrete, and its small spherical particles make the concrete mixture more workable (Pei-wei et al., 2007). Extensive research and development works have been done on the use of fly ash as a component of concrete (Aitcin and Laplante, 1992; Fernández-Jiménez et al., 2006; Chindaprasirt et al., 2007), and on the changes that its incorporation induces in both mechanical (Topcu and Canbaz, 2007) and thermal (Demirboga, 2007) properties. Moreover, Lingling et al. (2005) found that fly ash improves the compressive strength of bricks and makes them more resistant to frost attack. Cicek and Tanriverdi (2007) also observed the positive effect of fly ash on the compressive strength of bricks.

There are some advantages of using fly ash as a raw material for bricks, such as the firing energy can be saved because of the carbon content in fly ash. Several studies have been carried out in Germany, England, and China to produce bricks from fly ash (Guler et al., 1995; Kalwa and Grylicki, 1983; Mukherji and Machhoya, 1993; Lingling et al., 2005). The above studies revealed that the use of fly ash in fired bricks as a replacement of clay effectively saves land and energy, and decreases environmental pollution. Kumar (2002; 2003) conducted studies to produce bricks (solid and hollow) and blocks (solid and hollow) using fly ash with lime and phosphogypsum. He found that bricks and blocks of sufficient strength can be produced from the fly ash-lime-phosphogypsum mixture. These bricks and blocks have the potential for use in place of conventional burnt clay bricks and blocks.

Recently, a research work has been carried out in the United States (Shon et al., 2008) to produce compressed earth bricks from stockpiled circulating fluidized bed combustion ashes (SCFBCA). Fluidized bed combustion is a method of coal burning on a bed of heated particles suspended in a gas flow stream. The bed acts as a fluid at sufficient flow rates, resulting in a rapid mixing of the particles. At low temperatures, the sulfur of the coal is first oxidized to SO_2. Ground limestone is then introduced into the fluidized bed combustion chamber to react with the sulfur oxides in the flue gases, thus minimizing their release into the atmosphere. The resulting by-products of this flue gas desulfurization reaction (fly ash, bottom ash, and gypsum) contain more calcium compounds and sulfur products than the ashes from the conventional combustion systems. Consequently, the levels of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3) are somewhat low. Because the ash is formed at a lower temperature, the resulting leafy or flaky by-products are different from those generated in the conventional processes. Shon et al. (2008) observed that SCFBCA can be used to manufacture low-cost compressed earth bricks, which are useful as a construction material. In addition, there is substantial scope to reduce the disposal problem caused by SCFBCA.

Phosphogypsum

Waste phosphogypsum (PG) is an industrial by-product of phosphate fertilizer production from phosphate ore or fluorapatite. The generation of PG is up to 280 million tons per annum throughout the world (Yang et al., 2009). Over 6 million tons of PG are produced per annum in India (Sing, 2002). There are other countries where PG is generated as a waste material. The average annual production of PG in Turkey is about 3 million tons (Degirmenci, 2008). In Korea, 30 million tons of PG are deposited as wastes (Mun et al., 2007). The average annual production of PG is over 22 million tons in China (Yang et al., 2009). The generation of PG poses various environmental as well as storage problems. PG is usually deposited in the open areas or dumped into river or sea. The lack of consumption possibility of PG causes landfill problem and environmental pollution (Degirmenci, 2008). Therefore, it will be worthy if PG can be used successfully in construction materials.

Untreated PG has the limited scope of utilization in construction materials due to the presence of undesirable impurities such as P_2O_5, fluorides, organic matter and alkalis (Sing and Garg, 1997; Garg et al., 1996). However, PG has been used as a set controller in the manufacture of portland cement substituting natural gypsum, as a secondary binder with lime and cement, in the production of artificial aggregates for soil and road stabilization, and as a raw material for wallboard and plaster after purification or calcination process (Pressler, 1984; Sing and Garg, 1997; Singh et al., 2003). A large volume of purified PG can be used by combining with fly ash and lime to produce construction materials such as bricks and blocks (Yang et al., 2009; Kumar, 2002; Kumar, 2003). Fly ash-lime-phosphogypsum bricks and blocks with suitable PG content have shown a better performance in strong sulfate environments (Kumar, 2003).

Granulated blast-furnace slag

Blast-furnace slag is obtained during the manufacture of iron and steel, and possesses inherent hydraulic properties. It can be utilized for making different types of construction materials. Some of the construction materials such as portland slag cement (Chopra and Tanjea, 1966) and super-sulfated cement (Chopra and Lal, 1961) are produced in India as well as in many industrially advanced countries. At present, a fairly large quantity of granulated blast-furnace slag is being consumed in the manufacture of portland slag and super-sulfated cements (Malhotra and Tehri, 1996). The use of ground granulated blast-furnace slag with cement improves the microstructure, final strength, and durability of hardened concrete (Aitcin and Laplante, 1992; Malhotra, 1987). Moreover, the research carried out using small briquettes (Malhotra and Tehri, 1993) revealed that good quality bricks can be produced by pressing the slag-lime mixture (Malhotra and Dave, 1992) at sufficiently low pressure. The manufacturing process is quite simple as it does not require firing or autoclaving. Yet significant strength is obtained by humid curing. Malhotra and Tehri (1996) conducted an experiment and observed that good quality bricks can be produced from the stipulated proportions of slag-lime mixture and sand without needing any firing or autoclaving, and specialized plant or machinery, thus saving energy and solving the problem of environmental degradation.

Waste steel slag

Steel slag is a by-product produced during the conversion of iron ore or scrap iron to steel. The mineralogical composition of steel slag changes with its chemical components. Olivine, merwinite, di-calcium silicate, tri-calcium silicate, tetra-calcium aluminoferrite, di-calcium ferrite, solid compound of CaO–FeO–MnO–MgO, and free CaO are the common minerals in steel slag (Shih et al., 2004). Shi and Qian (2000) found that the free CaO content increases the reactivity of steel slag. However, the high free CaO content in steel slag has shown to produce volume expansion problems (Tang, 1973; Sun, 1983; Shi and Day, 1999).

Waste steel slag can be used to produce construction materials such as cementitious pastes and bricks. Li and Sun (2000) used steel slag to produce combined-alkali-slag paste materials. Besides, the incorporation of steel slag facilitates the production of bricks. It reduces the firing temperature needed for brick production. However, the compressive strength and firing shrinkage would drop in the presence of slag (Shih et al., 2004). Nevertheless, these bricks can be used as third class bricks in construction industry.

Rice husk ash

Rice husk ash (RHA) is a by-product of rice milling industry. It is obtained by burning the husks of rice paddy.

The controlled burning of rice husks between 500 and 800°C produces non-crystalline amorphous RHA (Mehta and Monteiro, 1993; Malhotra, 1993). It is whitish or grey in color. The particles of RHA possess cellular structure with a very high surface area. RHA has 90–95% amorphous silica (Mehta, 1992). It possesses excellent pozzolanic activity due to high surface area and high silica content.

After Mehta's findings in 1973 (Mehta, 1992), the use of RHA in construction materials was accelerated. According to Givi et al. (2010), RHA can be used in mortar and concrete with a good workability. Ismail and Waliuddin (1996) made high-strength concrete with RHA. Moreover, Zhang and Malhotra (1996) produced high-performance concrete using RHA as a supplementary cementing material. As a part of composite cement, RHA can be used to produce normal-strength self-consolidating concrete (Nehdi et al., 2004). It can also be used for producing self-consolidating high-performance concrete with improved hardened properties and durability (Safiuddin, 2008). The use of RHA decreases the porosity, and thus improves the compressive, tensile and flexural strengths of concrete. RHA also improves the corrosion resistance and freeze-thaw durability of concrete (Zhang and Malhotra, 1996).

RHA can also be used successfully in other construction materials such as bricks and blocks without any degradation in the quality of products (Nasly and Yassin, 2009; Rahman, 1987, 1988). Rahman (1987, 1988) reported that the compressive strength of bricks is increased in the presence of RHA and therefore recommended the use of RHA bricks in load-bearing walls. He also showed that the absorption capacity of RHA bricks lies within the permissible limit (Rahman, 1988). Nasly and Yassin (2009) used RHA to develop innovative interlocking blocks for use in sustainable housing. They also obtained good compressive strength for the blocks incorporating RHA. Furthermore, Lertsatitthanakorn et al. (2009) showed that the RHA based sand-cement blocks reduce solar heat transfer, and thus result in a decreased room temperature due to lower thermal conductivity than the commercial clay bricks.

Palm oil fuel ash

Palm oil fuel ash (POFA) is an agro-waste resulting from the combustion of oil palm plant residue in palm oil industry. Malaysia, Indonesia and Thailand are the main producers of palm oil, which is a leading agricultural cash crop in these tropical countries. After the extraction of oil from oil palm fruit, both husks and shells are burnt in boiler to produce steam for the turbine engine, which generates electricity for use in palm oil mills (Mahlia et al., 2001). After burning, the resulting ash, known as POFA, is generally disposed of in open fields, thus creating environmental and health problems (Tonnayopas et al., 2006). In order to find the solution to these problems, several studies were conducted to examine the feasibility of using POFA in construction materials.

Starting from 1990, many researchers reported that properly processed POFA is adequately reactive and possesses good pozzolanic activity (Abdullah et al., 2006; Sata et al., 2004; Hussin and Awal, 1997), and therefore can be used successfully as a supplementary cementing material for the production of concrete. Tay (1990) used unground POFA to partially replace ordinary portland cement (OPC) and showed that unground POFA shall not be used with a content higher than 10% of cement by weight due to its low pozzolanic property. Hussin and Ishida (1999) used 20 – 40% ground POFA by weight of OPC in concrete. They found that the compressive strength, modulus of elasticity, Poisson's ratio, shrinkage and creep of concrete were comparable to that of OPC concrete up to 30% replacement of cement. In addition, Hussin and Awal (1996, 1997) had shown that it is possible to use 40% ground POFA without affecting the concrete strength. It was also shown that the POFA concrete is sufficiently durable in addition to having a good strength. According to Sumadi and Hussin (1995), ground POFA can be used up to 20% cement replacement level with a durability factor at least comparable to that of OPC concrete. Ground POFA had shown good resistance to expansion due to sulfate attack (Awal and Hussin, 1997a; Jaturapitakkul et al., 2007) and alkali-silica reaction (Awal and Hussin, 1997b).

POFA has been used not only in normal concrete but also in special concretes such as high-strength, high-performance, and aerated concretes. Sata et al. (2004) made high-strength concrete with POFA and showed that the concrete containing up to 30% ground POFA provided a higher compressive strength than OPC concrete at later ages. Awal and Hussin (1999) used POFA to produce high-performance concrete with reasonably a good durability. In addition, Abdullah et al. (2006), and Hussin and Abdullah (2009) used ground POFA in aerated concrete. Thus, the published literature shows that POFA has a good potential for the production of different types of concrete.

The recent research studies show that POFA can also be used in other construction materials such as bricks and stone mastic asphalt (Ismail et al., 2010; Kamaluddin, 2008; Nasly and Yassin, 2009). Ismail et al. (2010) produced bricks with satisfactory compressive strength using POFA and paper sludge. Nasly and Yassin (2009) mentioned that POFA can be incorporated in interlocking blocks for use in sustainable housing. Besides, Kamaluddin (2008) used POFA as a filler material to produce stone mastic asphalt with enhanced stability, stiffness, and tensile strength.

Waste glass

A highly transparent material produced by melting a mixture of silica, soda, ash and $CaCO_3$ at high temperature, and then by cooling the melted mixture for solidification without crystallization is known as glass. Glass has proven its importance in our lives through manufactured products such as sheet glass, bottles, glassware, and vacuum tubing (Park et al., 2004). However, it is not biodegradable and therefore creates a problem for solid waste disposal. The disposal into landfills also does not provide any environment-friendly solution (Shao et al., 2000). Hence, the use of waste glass in construction materials can be a worthy solution to the environmental problem caused by this solid waste.

A clean dry glass powder is useful as a substitute for portland cement in concrete. The finely ground glass having a particle size finer than 38 μm contain a high amount of amorphous silica, which exhibits a pozzolanic behavior (Shao et al., 2000). Hence, the use of ground glass in concrete can be advantageous with respect to hardened properties and durability. Moreover, using waste glass as fine aggregate would produce better workability in concrete, provided its geometry is almost spherical and preferable to produce a workable mixture (Topcu and Canbaz, 2004). A high amount of waste glass decreases the unit weight of concrete (Topcu and Canbaz, 2004). The testing of mortar bar demonstrated that the finely ground glass helps to reduce the expansion due to alkali-silica reaction by up to 50% (Shao et al., 2000).

Demir (2009) investigated the effect of waste glass addition on the properties of fired clay brick. The compressive strength of the fired samples was significantly improved by the addition of waste glass. The amorphous nature of waste glass particles enhances the sintering action, which leads to achieving a better strength in bricks (Demir, 2009). The waste glass can be mixed with clay in different proportions to prepare high quality bricks. Clay bricks with suitable physical and mechanical properties can be obtained at a proper firing temperature by using waste glass with a content in the range of 15 to 30% by weight of clay (Loryuenyong et al., 2009). In a recent research by Chidiac and Federico (2007), the strength and transport properties of clay bricks were found to improve as a result of the improvement of pore structure when 15% (by weight of clay) of both fine and coarse waste glasses was added.

The possibility of producing paving blocks having various levels of fine or coarse waste glass in place of fine aggregate was also investigated (Turgut and Yahlizade, 2009). The use of fine glass as 20% replacement of fine aggregate by weight has a potential to produce good quality paving blocks. In addition, Dondi et al. (2009) showed that roof tiles as well as clay bricks can be produced by recycling the PC and TV waste glasses. They observed that the addition of PC and TV waste glass up to 2% by weight of clay does not significantly affect the performance of fired clay products. In contrast, the addition of 5% PC and TV waste glass may have deleterious effects, particularly on the strength of clay products.

Organic fibers

Organic fibers can be produced from a number of solid wastes such as bamboo, coconut, date palm, oil palm, sugar palm, sugarcane, and vegetable wastes. Some of these fibers are chemically more inert than either steel and glass fibers. They are also cheaper and more importantly most of them can be natural.

Bamboo fibers can be extracted from the bamboo wastes. This kind of fibers is useful to produce polymeric composites such as bamboo fiber reinforced plastic and polyester composites (Jain and Kumar, 1994; Deshpande et al., 2000). Jain and Kumar (1994) reported that bamboo fiber reinforced plastic composite can be used in a number of applications as a suitable replacement for the commercially available glass fiber reinforced plastic (GFRP) composite.

Coconut fibers can be used with portland cement to manufacture fiber-cement board. In a recent research, coconut fibers were used in reinforced concrete beam along with rice husk and sugarcane waste fibers (Sivaraja and Kandasamy, 2009). The performance of composite beam was evaluated under monotonic loading and compared with conventional concrete beam. It was found that the beam’s resistance to cracking due to seismic load improved in structural systems.

Date palm has a fibrous structure consisting of four types of fiber. They are leaf fibers in the peduncle, baste fibers in the stem, wood fibers in the trunk and surface fibers around the trunk, which can be utilized to produce construction products. It was observed that the flexural strength and toughness improve whereas the compressive strength decreases with the increased length and percentage of date palm fibers (Kriker et al., 2005).

Oil palm fiber is a non-hazardous biodegradable material extracted from oil palm's empty fruit bunch through decoration process. The palm fibers are clean, non-carcinogenic, and free from pesticides and soft parenchyma cells. These fibers are versatile as well as stable and can be processed into various dimensional grades to suit specific applications such as erosion control, soil stabilization, ceramic and brick manufacturing, flat board manufacturing, acoustics control, etc.

Sugar palm fiber is obtained as a by-product of the sugar palm plantation. This is also known as arenga pinnata fiber. The fiber is extracted from the trunk and leaf-bases of sugar palm plant. It is extremely durable, particularly when extracted from the leaf-bases surrounding the stem of sugar palm plant. Suger palm fiber offers good tensile and flexural properties in polymeric composites due to a better bonding with the matrix (Bachtiar et al., 2010; Sastra et al., 2005). Sastra et al. (2005) reported that the sugar palm or arenga pinnata fiber can successfully develop a beneficial polymeric composite with respect to rigidity when it is mixed as a reinforcement agent with the epoxy matrix.

Vegetable fibers have also been utilized to produce bricks for use as a construction material (Binci et al., 2005). The use of vegetable fibers reduces the dead weight and material handling cost of brick production. Binci et al. (2005) found that the vegetable fibers can increase the compressive strength and earthquake resistance due to increased interface layer.

Quarry waste

Quarry waste is obtained as a by-product during the production of aggregates through the crushing process of rocks in rubble crusher units. Using quarry waste as a substitute of sand in construction materials would resolve the environmental problems caused by the large-scale depletion of the natural sources of river and mining sands (Ilangovana et al., 2008). In addition, quarry waste can be a profitable alternative to the natural sands when the overall construction cost increases due to the transportation of sands from their sources (Safiuddin et al., 2007a).

Usually quarry waste is used in large scale as a surface finishing material in highways. Rezende and Carvalho (2003) used this waste as the main construction material for the base layer of flexible pavement and observed its satisfactory performance under field conditions. Quarry waste has also good potential for producing normal and lightweight concretes. Safiuddin et al. (2007a) reported that the workability of fresh concrete is increased, whereas the unit weight and air content remain unaffected in the presence of quarry waste. They also showed that the use of quarry waste does not affect the compressive strength, ultrasonic pulse velocity and elastic modulus of concrete; however, the initial surface absorption can be increased marginally. In addition, Ilangovana et al. (2008) reported that the permeability is lower whereas water absorption is higher than those of conventional concrete. Hence, the durability of concrete could be affected if quarry waste is used with a greater amount. Nevertheless, the durability-related properties of concrete can be improved using quarry waste in the presence of silica fume (Safiuddin et al., 2007b).

Hameed and Sekar (2009) studied the feasibility of using quarry waste and marble sludge in concrete. They found that the compressive and splitting tensile strengths and durability of concrete including quarry waste were better as compared with the conventional concrete. The concrete resistance to sulfate attack was enhanced, the permeability was decreased, but its water absorption became slightly higher than that of conventional concrete. These results suggest that the quarry waste can be used to produce adequately durable concrete.

Quarry waste can also be used in special concretes such as high-performance and self-consolidating concretes. Safiuddin et al. (2000a, b) produced high-performance concrete using quarry waste as a partial replacement of sand. Ho et al. (2002) included quarry waste in self-consolidating concrete to improve its self-compactability with enhanced workability properties. In addition, Felekoglu (2007) showed that a reasonable amount of limestone quarry waste can be used in self-consolidating concrete without affecting its compressive strength. Thus, the successful utilization of quarry waste in high-performance and self-consolidating concretes could turn this waste material into a valuable resource.

Construction and demolition debris

Huge quantity of construction and demolition (C&D) debris is produced during the construction and development works. As the construction industry grows, it generates more and more C&D debris, which create a major portion of solid wastes. The amount and type of C&D debris depend on many factors such as the stage of construction, type of construction work, and nature of construction practice on site. Most of the C&D debris are generally disposed of in landfills or openly dumped into uncontrolled waste pits and open areas (Rao et al., 2007). Therefore, the continuous industrial development would pose a serious disposal problem of C&D debris (Topcu and Guncan, 1995). The use of C&D debris in construction materials could ease the process of waste management.

The C&D debris generally comprise a larger portion of concrete rubble. Bricks, tiles, sand, dust, timber, plastics, cardboard, paper, and metals are also the constituents of C&D debris. After separation from other C&D debris, the concrete rubble can be crushed and used as a substitute for natural coarse aggregates. The processed concrete rubble is now well-known as recycled concrete aggregate (RCA). It can be utilized in producing concrete (Collins, 1994). RCA can also be used in road and airport pavement constructions (GTAA, 2007; Sherwood, 1995).

In addition, RCA can be used for making good structural concrete with the addition of fly ash, condensed silica fume, etc. (Rao et al., 2007). The properties of expected structural concrete can be improved by an appropriate quality control of RCA.

Rubber tires

Rubber tires are a ductile, non-biodegradable material that can exist for a long time without any degradation. The growing amount of waste rubber tires has resulted in an environmental problem (Li et al., 1998). In several countries, open burning and using as a fuel are considered the easiest way to get rid of the waste rubber tires, even though these processes lead to a very serious health hazard. Since the waste rubber tires cannot be biodegradable even after a long period of landfill treatment, material and energy recoveries are viable alternative to the disposal of this solid waste (Segre and Joekes, 2000).

Several investigations were carried out on the use of scrap tire particles in portland cement concrete. The processed rubber tires were used to replace fine and coarse aggregates depending on the fineness of particles (Li et al., 1998). As concrete has become the most widely used construction material, the incorporation of rubber tire particles in concrete would be a very good and promising way to utilize the large quantities of waste rubber. The use of scrap rubber tire particles in concrete would not only make a good use of such waste materials but also help to improve some concrete properties. The rubberized concrete shows excellent flexibility, ductility and energy absorbency as compared with conventional concrete (Li et al., 1998; Topcu, 1995). Furthermore, the tire rubber is preferable for use in self-consolidating concrete since it effectively interacts with cement matrix to produce high flowability along with good cohesiveness (Bignozzi and Sandrolini, 2006).

OTHER SOLID WASTES AND THEIR POTENTIAL USE IN CONSTRUCTION MATERIALS

Textile effluent treatment plant (ETP) sludge is a waste material produced from textile industry. Balasubramanian et al. (2006) revealed that the use of textile ETP up to 30% substitution of cement may be possible in the manufacturing of non-structural construction materials although the addition of sludge delays the setting process of cement. Kavas (2006) carried out a research to use boron waste in red mud brick production. He found that the mechanical performance of bricks is enhanced considerably due to the addition of boron waste. The recent research studies revealed that waste tea (Demir, 2006), waste ceramic tiles (Ay and Unal, 2000), cotton and limestone powder wastes (Algin and Turgut, 2008), and Kraft pulp production residues (Demir et al., 2005) can also be used in brick production.

USE OF SOLID WASTE BASED CONSTRUCTION MATERIALS IN REAL CONSTRUCTION

Significant research studies have been conducted on the development of new construction materials using different kinds of solid waste. However, the application of these construction materials in real construction is limited. More research is needed to study the actual behavior or performance of solid waste based construction materials under field conditions to encourage their practical applications. Table 3 shows some examples on the application of a number of solid waste based construction materials in real construction.

RESEARCH NEEDS

The use of solid wastes is manifold. They can be used as coarse aggregates, fine aggregates, or supplementary cementing material for the production of construction materials. Many research studies had been conducted utilizing solid wastes. Most of these research works focused the effects of solid wastes on the physical and mechanical properties of construction products. Some of those studies attempted to investigate the durability performance of several construction materials including solid wastes. However, more research is needed to confirm the beneficial effects of solid wastes on the key properties and durability of new construction products. In this context, the following research needs have been identified for further investigation to enforce the use of solid wastes in construction materials:

1. Commercial utilization of different solid wastes in the production of construction materials.
2. Optimization of the content of various solid wastes to produce sound and useful construction materials.
3. Comprehensive investigation on the potential use of different solid wastes to produce load-bearing construction materials.
4. Feasibility assessment for using various solid wastes in the production of environment-friendly and sustainable construction materials.
5. Systematic investigation of the effects of different solid wastes on the durability performance of construction products under various exposure conditions.
6. Examination of the possibility of using various solid wastes in higher grade construction materials.
7. Cost-benefit analysis of the solid waste based

Table 3. Application of solid waste based construction materials in real construction.

S/No.	Name of solid waste	Construction materials	Application in real construction
1	Fly ash	High-performance concrete	Water Tower Place, Chicago, USA (Aitcin and Laplante, 1992)
2	Bottom ash	Aggregates	Sub-base of a road section, Brest, France (Bruder-Hubscher et al., 2001)
3	Ground granulated blast-furnace slag	High-performance concrete	The Scotia Plaza, Toronto, Canada (Aitcin and Laplante, 1992)
4	Rice husk ash	Interlocking blocks	Sustainable housing in Malaysia (Nasly and Yassin, 2009)
5	Palm oil fuel ash	Interlocking blocks	Sustainable housing in Malaysia (Nasly and Yassin, 2009)
6	Bamboo fiber	Bamboo fiber reinforced plastic composite	Low cost housing in India (Jain and Kumar, 1994)
7	Quarry waste	Aggregates	Base layer of flexible pavement, Sobradinho, Brasilia, Brazil (Rezende and Carvalho, 2003)
8	Construction and demolition debris	Recycled concrete aggregate	Apron sub-base of Terminal 2, Lester B. Pearson International Air Port, Toronto, Canada (GTAA, 2007)

construction materials considering their lifetime performance.

8. Evaluation of the behavior or performance of solid waste based construction materials in real construction.

CONCLUDING REMARKS

During different industrial, mining, agricultural and domestic activities, huge quantity of solid wastes are being generated as by-products, which pose major environmental problems as well as occupy a large area of lands for their storage/disposal. There is a tremendous scope for setting up secondary industries for recycling and using such huge quantity of solid wastes as minerals or resources in the production of construction materials. Environment-friendly, energy-efficient, and cost-effective alternative materials produced from solid wastes will show a good market potential to fulfill people's needs in rural and urban areas. To effectively utilize the solid wastes in producing alternative construction materials, the detailed physico-chemical, engineering, thermal, mineralogical and morphological properties of these wastes need to be evaluated with good accuracy. The construction products from solid wastes practically will not be useful despite their good mechanical properties if the durability performance is not satisfactory. Therefore, rigorous quality control and assurance should be practiced for durability improvement while using solid wastes in construction materials. In addition, the impact of solid wastes on the durability performance of construction materials must be properly assessed before commercialization. The performance of solid waste based construction materials in real construction must also be evaluated prior to setting up secondary industries for recycling and utilization of solid wastes.

In order to maximize the use of alternative construction materials produced from different types of solid waste and to make the lab-based production processes feasible in real world, the technology-enabling centers are needed to facilitate entrepreneurs for effective commercialization. Good mechanical and durability performance of the newer products, dissemination of technologies emphasizing cost-benefit analysis, and feasibility assessment report will significantly contribute to the successful commercialization of the innovative processes. The alternative construction materials obtained from industrial, agro-industrial and mining solid wastes have ample scope for introducing new building components that will reduce the cost of construction to some extent. Therefore, the entrepreneurs and construction agencies must be encouraged to develop new products and processes using the solid wastes as raw materials, thus paving the innovative way for setting up secondary industries.

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