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The Circular Economy of Dharavi: Making building materials from waste

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Abstract

As developing nations continue to progress, people of these countries face problems of shortages in building materials and rising production of solid waste. The purpose of this research is to explore the potential of establishing a circular economy by recycling/reusing solid waste as alternative building materials. Focused on the slum of Dharavi in Mumbai, a settlement well-known for its existing recycling business, this article explores the concept of a circular economy utilizing local informal labor by considering the flow of waste materials in the slum. This article presents an analysis of the case studies where waste is reused as a building product and identifies the gaps, advantages, and disadvantages related to how and where the building materials from the case studies could be adapted in the context of the Dharavi slum.

Keywords: circular economy, building materials from waste, informal housing.

1. INTRODUCTION

1.1 Problem Statement

The building industries in developing nations are burdened with the problems of scarcity of financial and material resources (Razvi 2002). The volume of physical resources needed to develop infrastructure to meet the rising standard of living of the middle class puts severe pressure on the resources of a country. Moreover, the rapid urbanization causes shortages of standard housing, rapid depletion of natural resources such as forests and fertile agricultural land, air and water pollution, and increased waste production in the urban areas (Ofori 2000) It also causes high consumption rates leading to massive production of waste sent to landfills. Only a small fraction of the industrial waste from landfills is recycled while the rest is a loss of natural resources and embodied energy. Some of the waste is even sent to incineration plants,

which adds to the problem of air contamination with toxic fumes as well as greenhouse gases (GhG) associated with global climate change. The existing linear model catering to increased consumption is unsustainable, negatively affecting ecological balance as well as the welfare of the people.

The global report by the United Nations Centre for Human Settlements (United Nations Centre for Human Settlements 1996) points out that the problematic condition of human settlement urgently needs creative innovation and action. This change can be achieved by moving away from existing linear wasteful living standards. This calls for investigation into alternative building technologies using solid waste to address the problems mentioned before. Alternative building technologies from solid waste diminish dependency on raw and natural resources for construction material by utilizing locally available materials with the help of the local skills and labor, creating jobs

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in the process, and reducing the negative impact on the environment.

1.2 Significance of Research

This article analyzes the concept of a circular economy of building materials in the context of Dharavi, an informal slum in the heart of the metropolitan city of Mumbai, India. Dharavi faces problems of urbanization - the lack of housing infrastructure and proper living conditions. It has an informal market parallel to the formal economy of the city that is estimated to be around one billion dollars annually (Chandran 2016). Dharavi is selected for investigation because it has a thriving informal recycling business of inorganic waste.

Considering the established circular economy of recycling and reuse, this research investigates the scope and possibilities of recycling Dharavi's waste stream into recycled building materials. The research is about making a holistic case for Dharavi's contribution to a circular economy of building products, and delineating future steps needed to make this transition, which can be applied to other informal settlements.

2. METHODOLOGY

The concept of a circular economy presents a possible method to tackle the associated problems mentioned, having far-reaching positive social, environmental, and economic impacts. Circular economy is a broad concept whose principles advocate a holistic view of the opportunities that exist in the existing flow of resources and information that can turn into a closed loop network, mutually benefitting various individual stakeholders in every network. The smaller the loop established, the better the result. The smaller loops may have overlapping activities and once the smaller loops are established, the potential of the byproducts of the loop to connect with another resource cycle can be realized, which culminates into a broader complex network of circular loops. The *Caviar to Cardboard Project* by Graham Wiles serves as a good example of how smaller loops turn into a complex network of a loop having positive benefits in each cycle (Benyus 2002).

Studying the potential of Dharavi's contribution to a circular economy of building materials from recyclable waste that flows through the slum, this research first investigates existing buildings, living and working conditions, the construction methods and materials used, the types of business practiced, and the

problems faced. Second, the construction materials of the houses in Dharavi are investigated through a review of secondary sources and a tour of Dharavi in December 2017. Third, interaction with members of the organization URBZ Mumbai and SPARC have helped to further analyze the details of housing as well as some of the social issues related to the dwellings. These parts of the investigation culminate in an inventory of the main materials used to build the neighborhood's makeshift houses, as well as a list of the dry waste that the people recycle or reuse to earn their livelihood.

As a parallel strand, the investigation looks at case studies where an alternative building technology is made from recycled or waste components. The case study building materials are analyzed only in terms of the certain factors of suitability of the product, the ease of production, potential to contribute to an external market, and the technological knowledge available. A quantitative cost-based analysis is not done due to ambiguities of the stakeholders needed to implement the value chain of the circular loop and the cost of labor and machinery. In summary, this research provides the information needed to understand the advantages, factors and the obstacles involved in initiating a closed-loop material process as well as the potential stakeholders who can contribute to the system.

3. CIRCULAR ECONOMY CONTEXTUALIZED TO INDIA

3.1 Rethinking a Circular Indian Economy

India faces new challenges in terms of resources and energy management due to its high economic growth and large population. It is necessary for the country to tackle the issues of erosion of natural capital, greenhouse gas emissions, and waste generation. A circular model of growth could help India achieve its developmental goals by involving both the formal and the informal sector. According to a 2016 Ellen MacArthur Foundation report - *Circular Economy of India: Rethinking Growth for Long-Term Prosperity* - as the economy of the country develops, these informal recycling practices will become less attractive unless a more systematic approach is taken to include them in the value chain. Moreover, as India becomes connected to the global market's linear supply chains, as practiced mostly in the developed economies, the problems of loss of resources and waste generation will be aggravated.

The report identified three focus areas and provided recommendations where circular economies could have a beneficial impact. The three areas identified were food and agriculture, mobility and vehicle manufacturing, and cities and construction (Ellen MacArthur Foundation 2016).

The construction sector is one of the highest consumers of resources. It has grown at a rate of 10 percent over the last decade. The main materials used in construction in India are sand, stone aggregates, soil for bricks and limestone for concrete. According to the report *Material Consumption Patterns in India* by GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), five critical building resources were identified based on factors such as scarcity, cost, environmental impact, embodied energy, supply risk, lack of recyclability, and conflict of use. The five materials were sand, soil, stone, limestone, and metals such as iron and steel. The construction industry will face serious material supply problems if the current growth trend continues. The construction sector is most vulnerable to market volatility since the cost of a building is associated with material costs. Thus, emphasis is needed on resource efficiency and alternative building materials to support the industry.

A major portion of solid waste in India is being managed informally and a case for a circular model could be made whereby waste is being used as a resource for building products. The recycling of waste is a labor-intensive service, and it is important to consider the recycling effort in a formal supply chain of products used to make building materials. A collaborative and concerted effort is needed both from the formal and the informal sector in making decisions about how to utilize the resources from waste responsibly into a building material. It would also create new employment opportunities. The safety of the workers involved in this industry should be of paramount importance, and safety needs to be reinforced by implementing policies and regulations discouraging actions that have harmful human effects. Thus, the toxicity of the materials

during production or use need to be analyzed for their material composition, and necessary protective actions must be taken to prevent any negative effects on human health or on the environment. Identification of tighter and smaller loops would require an information exchange platform where digital technologies could be useful. Tighter loops have the most environmental benefits and create local employment

opportunities (Stahel 2015). The informal sector is one of the major stakeholders involved and an implementation of a circular loop would require active participation of the informal sector.

4. DHARAVI

4.1 The Construction of Houses In Dharavi

Dharavi covers an area of 525 acres. The population density in Dharavi is estimated to be in the range of 270,000–450,000 inhabitants per square km. (Boano, William and Newton 2013). The total estimated population is around 1,000,000 people (Habitat for Humanity Great Britain 2017). It has around 15,000 single room factories employing around a quarter million people housed in single room tenements. Spaces are multifunctional, and flexibility is a key to their living. During the day, the ground floor is used for small businesses and shops; at night, some workers may sleep in the shops with the family members in the upper stories. The median floor areas are typically 10 square meters with each unit housing an average of five to six people (Baweja 2015). There are no formal living areas. Most people have no sanitation infrastructure and sometimes people must buy water for their use from water sellers. There is only one public toilet per approximately 1500 residents. The space for a private bath is a dream for many and some use the kitchen space as a bath area. Most of the rooms have a cooking gas stove and access to electricity (BBC News n.d.).

The houses of Dharavi range in quality, from temporary shanties made from bamboo, wooden sticks, and corrugated metal sheets to houses made of more permanent materials such as brick, mortar, and concrete. The range of materials used for housing are bricks, wood, concrete, rusted iron, steel I-section beams; ceramic, slate, and clay tiles; asbestos and tarpaulin sheets. The houses in Dharavi are financed incrementally over decades moving from temporary to more permanent construction with bricks and cement.

Initially the houses start on normal ground with bamboo or wooden sticks embedded into the earth which forms the frame on which tin sheets are placed to act as a wall. The tin or asbestos sheets are also used as the roofing material. The thin metal sheets have poor heat resistivity and create extremely hot indoor temperatures during the day. Some metal skins also come from discarded metal drums which are spread out to form flat metal sheets. Moreover, due to improper overlapping of the tin sheets and perforations of the

sheets because of rusting, water penetrates through the roof and walls during the monsoon period. To counter the effects of water penetration, the dwellers use blue tarpaulin sheets or other available plastic sheets to cover the roof. The asbestos sheet does provide protection from the thermal heat, but it is a known carcinogenic material. If overtime the family performs well financially, the tin walls get replaced with brick-and-mortar walls. This transformation of the walls is gradual where one wall may be replaced in one year while the other walls are replaced gradually in the subsequent years. As families grow, there is a need for the people to build higher to two or three stories, but this vertical transformation is not an easy transformation due to the legal and social issues of the space. Sometimes this space is rented to other families as living or working space.

The addition of the upper floors uses metal I-beams placed on top of the load-bearing brick wall, which usually spans one-way three to four meters between the walls. Typically, two-by-two-foot gray slate square tiles are placed between the steel, dictating the spacing of the steel beams (Dovey and Tomlinson 2012). Cement screeds are applied on top of the slate to form the floor. The roofing structure is either wooden sticks or I-beams. Sometimes trusses are formed for longer spans (Dovey and Tomlinson 2012). Generally, corrugated sheet metal is used on the roof as concrete slabs are hard to afford. Access to upper stories is accomplished by using a metal or a wooden ladder from a common street allowing flexibility for renting out the space. Most windows do not use glass panes. Instead, they have a grill box projecting from the outer wall, which provides extra space for keeping household items. Flexibility of working and living space is maximized using lofts, stackable mattresses, and folding tables.

The addition of the second and third floor is completed with the help of a local craftsman with previous construction experience and skills to build the additional floor (sP+a and URBZ 2015). These construction processes are performed on a local basis and do not involve governmental registration or legal authorization. The construction of reinforced slabs, walls, and columns is legally forbidden as is building a toilet inside. But these legal hurdles can be bypassed if informal revenue is paid to the local police. The craftsman is usually local, aware of rules (flexibility and restrictions), and well connected with the local municipal officers.

The transformation of houses has been studied based on the author's visit to the slum and on reviewing secondary sources and articles, and pictures and videos of Dharavi. High quality images of the houses at the edge of Dharavi in "60 Feet Road: Bhatiya Nagar facades: Dharavi, Mumbai, Maharashtra, India" by Robert Polidori helped to investigate the details of construction. To understand the growth, a report named "Incremental: A Study of Informal Incrementality, Its Impacting Factors and Supporting Systems", published by the organization SPARC provided additional information, and parallels have been drawn from it to understand the informal house construction in Dharavi (SPARC 2013). Figure 1 is the result of the first steps of the investigation: it shows the addition of different materials over time used for the incremental growth of the house.

Financing and availability of materials for housing is a major issue faced in the Dharavi slum. The recycling industry can address this issue by fulfilling the needs of the people by creating alternative building products that can offset or reduce the financing for procurement of materials. In addition, production of alternative building materials would serve to generate income for the slum dwellers. The walls and roof have immense opportunity for increased use of alternative building materials, with potential to increase thermal comfort and to eliminate rainwater penetration. An alternative to asbestos sheets for roofing needs to be explored to address health concerns. In addition to residential structures, building materials used to construct work sheds need to be improved since incessant rain during the monsoon season can halt work causing a loss of daily income (Campana 2013).

In her book, *Architecture for Rapid Change and Scarce Resources*, Sumita Sinha (2012) helps to develop the criteria for the appropriateness of new building technologies from waste materials. These are:

- Empower the dwellers to build higher or to maximize the utilization of space
- Provide thermal comfort and rainwater protection
- Products should aim to be affordable, and materials should be locally available

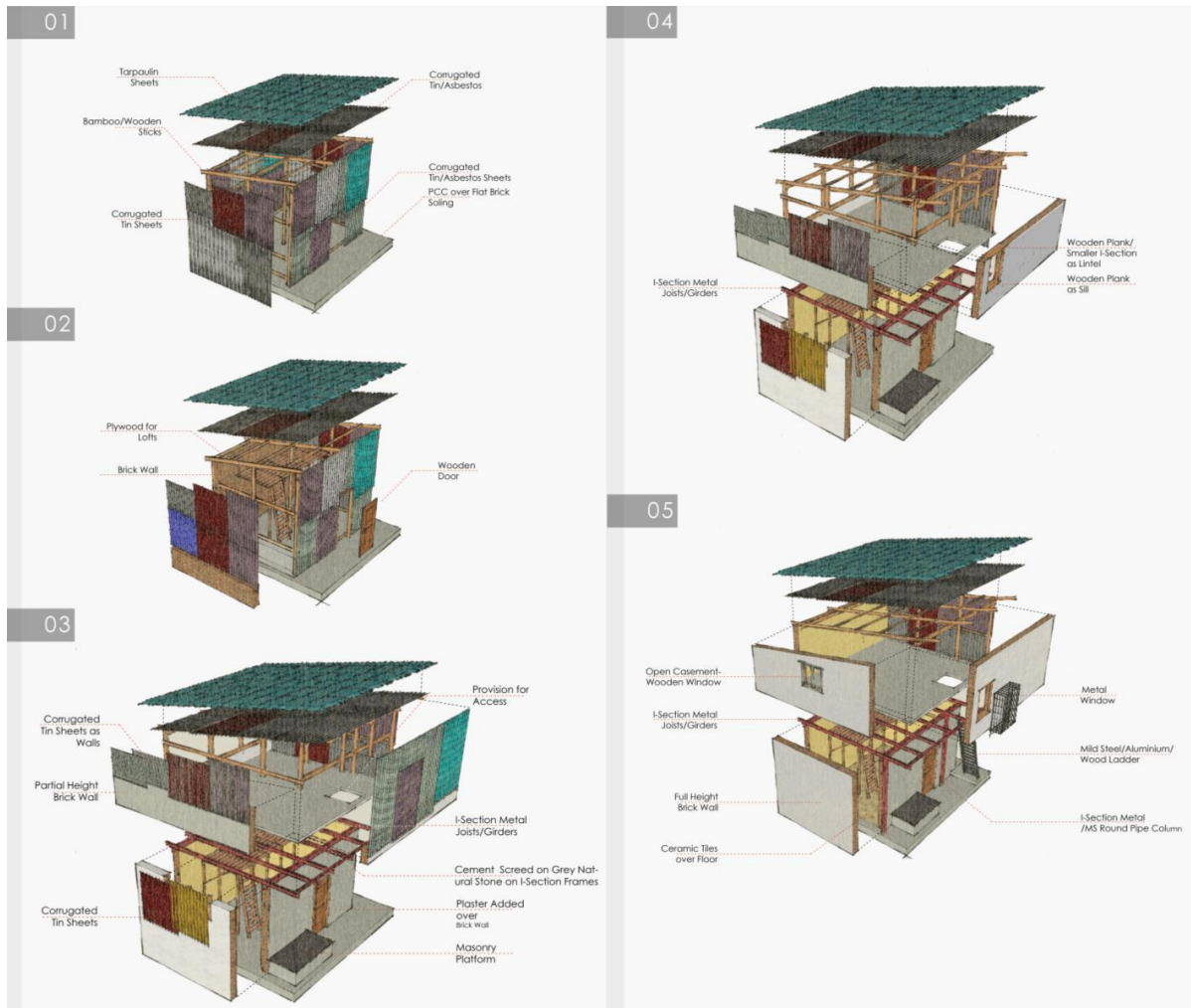


Figure 1. Incremental Growth of a House

- Production of the material should not be energy intensive, create more pollution, or create a demand for a product which is toxic in nature.
- Production should not involve large complex commercial processes and even if a machine is needed for its production, it is to be evaluated whether the local people could get access to such a machine preferably with the help a one- time investment from non-profit organizations
- Create an economy which benefits the local people
- Improve the conditions of life by improving housing

It will be difficult to satisfy all the mentioned criteria but satisfying most of the criteria will result in the most benefit in terms of producing a circular economy that addresses social and environmental concerns.

4.2 Entrepreneurship Culture

The retail, manufacturing, recycling, and wholesale supply chains operating out in Dharavi are estimated at \$US 660 million to a billion dollars annually (Yardley 2013). Most of the production and manufacturing in the slum are not registered. The industries in the slum consist of tanneries, pottery, textiles and tailoring, gold and jewelry, surgical thread, steel fabrication, and kite manufacturing along with other manufacturing that deal with a variety of food items such as

padam, chikki (a sweet made from peanuts and jaggery), and snacks (Day 2010). Dharavi is a thriving business center with thousands of micro-entrepreneurs who have created an invaluable industry of recycling. Economic activities are often linked with ethnic identities in the neighborhoods formed. Home based entrepreneurship is an essential element of the informal economy (Nijman 2010).

4.3 Waste Recycling

The informal economy along with the waste management industry out of this informal network is of interest to many scholars and entrepreneurs. Information about the informal economy contributes to an inventory of materials that flows through Dharavi. Dharavi has more than 1,200 units of waste recycling out of which 780 are plastic recycling (Pandey and Sharma 2014). Dharavi is known for its recycling. It is estimated to recycle about 80 percent of Mumbai's dry waste discarded by the city having a population of 19 million citizens. In Dharavi's recycling shacks people

sit in waist deep piles of car batteries, computer parts, fluorescent lights, plastic bags, paper, cardboard boxes, and wire hangers. Each item is sorted for recycling. Workshops have aluminum smelters for recycling drink cans. People stir huge vats of waste soap retrieved from rubbish tips and local hotels. One-gallon size oil cans are cleaned and hammered back into shape. Then they are sold back to the oil companies and local consumers (McDougall 2007) The 13th compound is an area where most of the recycling and scrap industry is concentrated, focusing on cotton scrap, iron scrap, glass products, empty tins, empty bottles, all sorts of plastic ranging from drums to bags. Recycling of the big blue plastic drums which are used for storage purposes is a big industry here.

The aim of this study is to propose opportunities for innovation and utilization of available waste resources combined with an initiation of entrepreneurial activities through the recycling industry of Dharavi. The existing economy, though it exhibits features of a circular economy, is not circular in the true sense

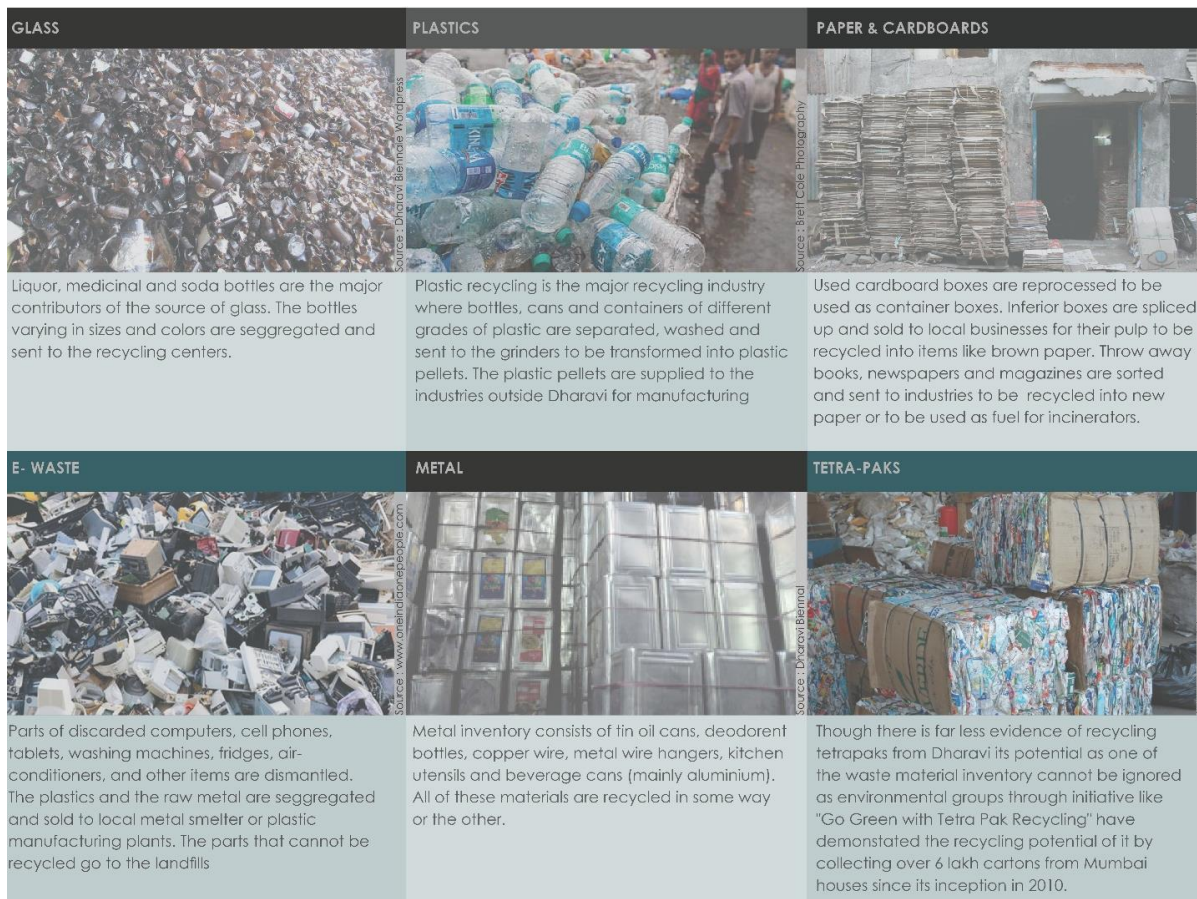


Figure 2. Existing Recycling Industries

since some of the industries are polluting and recycling is done at the cost of the health of the persons involved. To better understand applications for building materials created from Dharavi's existing material streams, examples of building materials from waste from around the world were explored.

5. CASE STUDIES OF BUILDING FROM WASTE

5.1 INTRODUCTION

The following section looks at various case studies of building materials from around the world experimented from waste whose first use was not a building product and those types of wastes which are available in the slum. Seven types of waste from which building materials have been made are identified and studied. They are 1) Plastic 2) Cardboard 3) Glass 4) Paper 5) Leather 6) Tetra-Pak and 7) E-waste. The list does not include scrap metal as a potential waste due to the lack of evidence of it being recycled into a building product. This research tries to gather information about the production processes of these materials, the material properties, the obstacles of recycling, and challenges involved. It is an analysis of the suitability of the case study building products to contribute to a circular economy in the context of Dharavi. It gives us a measure of difficulty to implement a case study building product in the context of Dharavi. This takes into consideration the appropriateness of material properties of the product to the existing housing situation, the production difficulties, possible demand of these products outside of Dharavi and whether the product needs any further development or research to make it more suitable to the local context. These factors help to identify any entrepreneur or social organizations about the issues or steps to take into consideration if a circular building industry is to be made in Dharavi, involving the people of Dharavi in the processes of collection, manufacturing, and production. This helps to understand the potential areas where research could be further conducted:

- by material scientists to improve the material qualities of the product or to test the strength characteristics of the product
- to identify the presence of any harmful elements in the material
- by architects and product designers to design the details of the product to make it adaptable to the needs of the context

5.2 Building Materials from Plastic Recycling

5.2.1 Plastic Lumber

Plastic lumber is mainly made from HDPE plastics. In the United States, this plastic lumber is mainly used in decking, railings, and furniture. The use of plastic lumber prevents deforestation and can be recycled again at the end of their original intended use. Thomas Nosker, a professor at Rutgers University, Department of Material Science and Engineering, developed a stronger plastic lumber from recycled plastic bottles, coffee cups, and other plastics which could be used to span bridges strong enough to support 120-ton locomotives. 1.5 million railway ties in the United States have been built using this. Fire retardants and machines for plastic lumber production have also been researched and technology developed (Nosker, Lynch and Richard 2012). Recycled HDPE planks developed earlier, showed the problems of sagging over time when load was applied. Polystyrene was later added to HDPE, which helped the material to gain strength. Plastic lumber has a durability advantage over wood. Moreover, wood is sometimes treated with toxic preservatives which could leach into soil and groundwater, while the structural plastic lumber does not pose such risks as it is mostly made from High Density Polyethylene reinforced with stiffer plastics or recycled composites such as car bumpers (Blesch and Bates 2016).

5.2.2 Plastic Wall Tile

The plastic tile is developed out of a research project led by S.K. Dhawan, a scientist at the National Physical Laboratory (NPL) in India (Vyawahare 2017). The tiles were demonstrated to be used as wall panels to create a bathroom sized room at an exhibition organized at Council of Scientific & Industrial Research (CSIR). The plastic items used in this product are mainly composed of a mixture of low-density plastic, high density plastic, polypropylene, and polystyrene. Plastic bags, bottles, milk packets, and sachets are used (Vyawahare 2017). A company named Shayna EcoUnified India Pvt. Ltd adapted the technology developed by CSIR-NPL to develop plastic tiles. The plastics are collected by the company from various sources comprising rag pickers, households, NGOs, and other institutions. The plastics are cleaned, sorted, shredded into flakes, heated and compressed into pellets. These pellets are then mixed with fillers and molded into tiles. For fire safety the company fly ash was added with other flame retardants to the product and UV retardant for protection against sun (Shayna EcoUnified 2017). Around 600 plastic bags are required to make one tile. As demonstrated at the

CSIR exhibition, the tiles are attached or nailed to a frame to comprise a room.

5.2.3 Plastic Roofing Tile

Water sachets, plastic bottles, and sawdust are the main ingredients used in plastic roofing tile. The study of recycling was done in Ogbomoso in Nigeria where plastic material from trenches, drainages, streets, dump sites, and eateries was collected (Temitope, et al. 2015). Development of plastic roofing tile from waste plastic was undertaken in response to growing pollution concerns of waste plastic, which causes blockage of drainage, suffocates animal life, prevents groundwater percolation, leaches toxic elements, and causes other harmful effects. For the Nigeria study, the plastics consisting of plastic bottles and water sachets were sorted and cleaned with detergent and water. The dried plastics were shredded. Shredded plastic was melted in an aluminum pot and dried Saw dust from mahogany and iroko tree was added. The blended mixture was poured into a wooden mold and knocked to remove entrapped bubbles which could cause a crack in the tile. The tile is then air cooled for 20 minutes. Various tests such as water absorption, crushing, flammability, and friction were conducted on the tile. There was no water absorption in the tile. The crushing strength of the plastic tile showed a 15% decrease in strength than a conventional tile. The composite flammability test by application of heat from oxy-acetylene gas also showed better results than conventional tiles, which split under flame, but no specific fire rating value was specified in the research (Temitope, et al. 2015).

5.2.4 Ubuntublox

Ubuntublox is a compressed block made from unsorted waste materials. The material was developed in response to the Haiti earthquake by the fence builder Harvey Lacey (Lacey n.d.) who invented a simple press to mechanically condense widely available plastic waste into building blocks. The apparatus is simple to use, can be locally built and carried by a single person. The prototypes were lightweight, at about 3 kg each, and successful from a structural point of view. However, Hebel et al (2014) posed an

economical question concerning Ubuntublox from plastic, since recycling centers in developing countries could potentially redeem these materials for their petroleum prices making the base material too valuable to be used as a block (Hebel, Wisniewska and Heisel 2014). This realization led to the search for alternative materials. Styrofoam and agricultural wastes were selected. The agricultural waste used for alternative materials consisted of remains of the Vetiver plant after processing of its oil. It is a waste product that is burnt with an accelerant, which releases pollutants into the atmosphere. Thus, the use of Vetiver plants in the block has positive environmental impacts. It is also an insect repellent, which makes it useful for the construction of homes. There are concerns, however, that blocks from agricultural waste may be less durable than those from plastic but there are concerns for the durability of the product made from agricultural waste. Therefore, for use in construction, block made from agricultural waste needs an extra water protection layer of plastic to make the envelope resistant to water penetration. Blocks made from either plastic or agricultural waste are lightweight, excellent insulators, and resistant to hurricanes and earthquakes (Lacey n.d.). Ubuntublox has been used for single story building. The standard size of the block is 200 mm x 400 mm and is load bearing in nature, withstanding a weight of 4,000 pounds. In construction, multiple courses require stiffening with rebar and wire and a heavy base of earthbags, concrete blocks or gravel bags must be provided. . . Fire resistance can be improved with a coating of stucco or plaster on steel chicken wire mesh, the assembly cannot withstand prolonged fire exposure.

5.2.5 Recycled Plastic Bricks

Recycled plastic bricks are developed by the architect Oscar Mendez in Bogota, Colombia¹. He formed a company called Conceptos Plasticos, which transforms plastic and rubber waste into construction materials such as bricks, beams, and pillars. Collection of the materials is done by encouraging schools and community groups. They also train and educate communities about building their own houses (Winkless 2016). The collected materials are segregated

¹ Small scale recycling is an established trade in Colombia. 40,000 small trucks and carts driven by people roam around the city and collect the solid wastes that are deemed to be recyclable. The recyclers bring the scrap metals, plastic bottles, and other plastic items to

a common shop where they are paid according to the weight of the materials. For bulk production, the plastics are brought from these shops

according to the type of plastic, and then cleaned and ground into fine powder. The plastics used for the recycled plastic bricks are sourced from household plastic waste, battery packaging, and electrical waste such as old computers and television sets (Al Jazeera English 2017). The different types of ground plastic are mixed according to a proportion that is a proprietary secret of the company. Additives are added to the plastic to make the bricks more heat resistant. The mixed plastic is poured into a mold and heated to exactly the melting point, around 200 to 240 degrees centigrade, so as not to burn the plastic and release toxic gases into the atmosphere. The heated mixture is compressed into brick shapes. The length of the plastic brick modules in Colombia is more than a foot long and may be close to two feet as estimated from the pictures. The design of the bricks is interlocking in nature such as LEGO blocks and do not require adhesives. The plastic brick walls are locked in on plastic beams by a kind of tongue and groove joints. The length of the plastic brick modules in Colombia is more than a foot long and may be close to two feet as estimated from the pictures and the video. It makes a strong durable structure resistant to earthquakes and fire. The company claims that it could serve as an alternative for wood construction, and thus the use of these plastic bricks could lead to less deforestation.

5.3 Building Materials from Cardboard

5.3.1 Corrugated Cardboard Pod

The corrugated cardboard pod is a housing project developed by Auburn University in 2001 using wax impregnated cardboard waste that cannot be recycled due to the wax content. Bales of corrugated cardboard are stacked, serving as a load bearing wall over which a heavy timber beam and a roof is built. The bales, wrapped in plastic, comprise the foundation, and a concrete base is poured over the bales to support the wall (Michler n.d.). The construction of the walls has a modular approach. The blocks are placed in a running bond pattern. Due to the high weight and friction between the blocks, additional reinforcement is unnecessary. The gaps between the bales are filled with soil, Portland Cement, and cardboard shavings. Cross bracing cables are used in the prototype to stabilize the structure (Hebel, Wisniewska and Heisel 2014). The standard dimensions of the blocks used were 800 mm x 2000 mm with a height of 700 mm.

The advantages are limited in this case. There is no evidence of how the block performs in rain and fire, but the fact that the prototype building still stands in

good shape shows that rain might not affect the building as much if it is protected by a large roof. A similar project, PHZ2 in Germany, also used thick walls made from cardboard paper, and only the first 8-10 cm of the wall were affected by precipitation, which dried out in a short time.

5.3.2 Modular Roof

ModRoof is a modular roofing system made from cardboard and agricultural waste, like coconut fiber. Founder Hasit Ganatra, an engineering graduate from the University of Southern California formed the company ReMaterials in India (REMATERIALS n.d.). The product serves as an alternative to metal or concrete roofing systems in India's slum settlements. The cardboard is shredded and then blended to pulp with the addition of water. Organic fibers are added for reinforcement and the final mixture is poured into a mold. It is compressed cold to extract the water forming the hardened panel. The panels are heated and, after drying, a specially developed waterproofing paint is added. The modular panel can be interlocked with surrounding panels, making it easy to install and maintain (Hebel, Wisniewska and Heisel 2014). In a slum community in Ahmedabad, the roof was available through a loan system. The roof is more expensive than corrugated metal sheets but cheaper than concrete construction. Customers used microfinance loans to buy the product (Rice 2017). A similar micro-financing scheme can be developed in Dharavi with the support of various non-profit organizations helping the people to fund the roofing materials.

5.4 Building Materials from Glass Recycling

5.4.1 Recycled Glass Tiles

Recycled glass tiles were produced out of a waste processing system named Waste Labs which created a process for local collection, processing, and transformation of waste in London. The recycled glass tile initiative was called Glass Lab, developed by a Royal College of Art student, Diana Simpson Hernandez. She was examining local resources and waste materials to produce alternative economies empowering businesses and communities. Glass, collected from local businesses, is crushed, cleaned, and sorted into fine, medium, and coarse filaments. The filaments are combined with a vegetable bio-resin binder to produce strong weatherproof materials such as tiles, bollards, and street furniture (Chang 2013) (Art 2021).

5.4.2 Recycled Glass Walls or Panels

Recycled glass wall panels use recycled glass from bottles for cladding purposes. Production involves a low-tech approach of recycling the glass waste of bottles diverted from landfills. The color of the glass cladding depends upon the colors of the bottles used. Patterns and artwork can also be created on the panels because the crushed glass is hand applied in the substrate. The resulting wall panels find application in luxurious and commercial settings (Alternative SURFACES n.d.). The hard and non-porous characteristics prevent mold and bacterial growth. They can serve as a cheap and durable alternative to quartz plastering. The glass can be broken down into similar dimensions to quartz and fixed into one-inch-thick slabs of white cement (Bahamon and Sanjinés 2010). A fine example of this was implemented in Casas Chorizo, housing in Buenos Aires, Argentina. The glass walls proved aesthetically pleasing and maintenance-free.

5.4.3 Waste Glass as Aggregate in Clay Brick

Waste glass, when added to clay, improves in some of the properties of clay brick used for wall construction. Testing was done at the Afyon Kocatepe University in Turkey (Demir 2009). Several samples with different mix proportions and kiln temperatures were studied and their effect on properties such as apparent porosity, bulk density, loss on ignition, water absorption, and compressive strength were noted. The size of the test specimen was 75 mm x 40 mm x 100 mm. Drying and firing shrinkage decreased with increasing amounts of waste glass, and thus it caused a positive effect of reducing any internal strain during the drying process. There was no change in bulk density with regards to the amount of waste added or the temperature of the kiln, but the apparent density of the samples fired at higher temperatures of 1050 °C was lower. The water absorption values decreased with increasing firing temperature and decreased with increasing amounts of waste glass. The compressive strength of a 10% glass mix is 12-14 % higher than 0% mix. The 10% mix fired at 1050° C demonstrated a compressive strength of 29.35 MPa (Demir 2009).

5.5 Building Materials from Paper Recycling

5.5.1 Newspaper Wood

Designer Mieke Meijer and the company Vij5, Netherlands, developed a simple method of converting waste paper into a composite material having wood-like properties. The paper waste is soaked in glue and

wrapped along a linear axis on a wooden log. The method mimics the circular rings of a tree log when it is cut. The material can be treated like construction lumber and can be drilled, cut, milled, and nailed (Hebel, Wisniewska and Heisel 2014). Waterproofing can be accomplished by applying a finish coat of varnish or wax. Any application for wooden boards can be achieved by this new material. The product does not aim to be a large-scale alternative to wood but is developed to tackle the surplus of waste newspaper to turn it into something useful. At the end of its lifecycle as a building material, the designer intended for it to be reprocessed through the same cycle. The maximum size of the log achieved is the size of an open newspaper, around 380 mm.

5.5.2 Papertile

Paper tile vault is a product developed by the BLOCK Research Group for use in their research of vaulting techniques (Hebel, Wisniewska and Heisel 2014). Paper and cardboard are used as the input construction material. Cardboard and paper are shredded and repulped by adding water. The liquid dissolves to form a mass that can be pressed to a desired shape. The combined material is known as papier mache and is compressed into brick tiles with the addition of an organic wheat starch paste before the process of pressing. The wheat starch paste increases the compressive strength. Thinner blocks take less time to dry. The final texture of the brick depends on the pulp of the paper used. The vault tiles can be glued together with mortar. Fireproofing can be done with the addition of layers or ingredients such as borates; waterproofing by varnishing (Hebel, Wisniewska and Heisel 2014).

5.6 Building Materials from Leather

5.6.1 Structural Skin

Waste leather is used to create a slat-like product used to make furniture products. This structural skin has wood-like properties, and the surface texture looks like marbled paper (Smow 2015). The product was developed by Spanish designer Jorge Penadés, a graduate from Madrid's Instituto Europeo de Design (IED) (Jones 2017). The manufacturing process in the leather industry leads to a significant amount of leather waste. The leather quality depends upon what part of the animal the materials came from, and the higher the movement the lower the quality (Materia 2015). This waste leather is shredded and then combined with bone glue as binder to form a lumber-

like product². The leather strips are added to the glue and then placed into iron molds to be compressed. The top layer is shaved to get a smooth appearance (Morby 2015). A coating of shellac is applied to finish the product. Initially the production of leather tiles was attempted, but it proved difficult to keep them flat (Penadés n.d.).

5.7 Building Materials from Tetra Pak

5.7.1 Tuff Roof

TUFF roof is a corrugated roofing sheet developed from Tetra Pak cartons by Daman Ganga Paper Mill in India (Hebel, Wisniewska and Heisel 2014). Tetra Pak consists of layers of cardboard, plastic films and aluminum foil which is difficult and expensive to segregate, and the machine needed to recycle Tetra Pak is not usually found in the developing world. The advantage of this material over corrugated metal or concrete panels is that it is non-corrosive, light, fire-proof, heat-reflective, and lower in production costs. Production consists of placing the shredded cartons in a mold and then applying heat to activate the inherent plastics, paraffin, and glues to act as the new adhesive. Finally, the heated material is compressed to achieve the corrugated shape (Hebel, Wisniewska and Heisel 2014).

Boards made from TUFF sheet material can also serve as wall panels, which would further improve the comfort conditions of the interior during the summer months. The material does not need fasteners for jointing and can be nailed. Though there is far less evidence of recycling Tetra Pak in Dharavi, its potential as a part of the waste material inventory cannot be ignored. Environmental groups, through initiatives such as "Go Green with Tetra Pak Recycling," have demonstrated, the recycling potential of Tetra Pak by collecting cartons from Mumbai houses since the products' inception in 2010 (Tetra Pak Association 2015).

5.8 Building Materials from E-Waste Recycling

5.8.1 Admixture in Cement Mortar from Printed Circuit Boards

Recycling of electronic waste is one of the most difficult processes compared to recycling of other

products. This is due to the diversity and volume of composite products of metals and non-metals, which are hard to extract using low-cost technology. Printed circuit boards (PCB) contain metals such as copper, aluminum, iron, gold, tin, antimony, lead, and tin, as well as non-metals consisting of thermosetting resins and glass fibers (Theo 1998). The amount of valuable metals in PCB drives the recycling and the recovery of metals. The separation of metals is done by smelting, pyrolysis, shredding, separation, and chemical treatment, which are extremely energy intensive. Extreme precautions are needed due to the high potential of exposure to toxic byproducts in dust and gas arising from the processes. Non-metals constitute about 70% of the materials in printed circuit boards (Veit, et al. 2005). The non-metals are conventionally incinerated or sent to the landfills causing adverse impacts on the environment. The non-metallic powder from the printed circuit board can be added as admixture to cement mortar in various proportions. It leads to a lower bulk density of cement and a higher air content, which is good for construction. There is a slight reduction in compressive strength (18%) and flexural strength (11%) and a negligible change in shrinkage rate. The strength decreases much more rapidly if the proportion of the mixture of non-metallic parts is increased more than 15%. A mix below 15% shows better water capillary control than a 0% mix and the admixture improve the water retention property of cement mortar (Wang, Zhang and Wang 2012).

The current trend of informal recycling of electronic waste is harmful to people and the environment and should not be encouraged until responsible protocols are put in place. Dharavi can only contribute to two types of labor for a circular economy of electronic waste. One is to sort the products to the appropriate recycling centers, and the other is to extract the products safely for further processing or extraction in a formal recycling center armed with proper gear and knowledge, supervised by chemical or metallurgical engineers. Initiatives such as the government authorized electronic waste recycler E-Parisaraa Pvt. Ltd in Bangalore could be implemented. The objective of E-Parisaraa is to create an opportunity to extract the raw materials such as metals, plastic, and glass from electronic waste using simple, cost-efficient

² Bone glue comes from the byproduct of meat processing. Bone is ground to powder, dissolved in water, and after boiling dried to form the bone glue.

environmentally friendly technologies suitable to Indian conditions (E-Parisaraa Private Limited 2005). It has major companies such as IBM, Tata Elxsi, ABB, HP, Infosys, Intel, Sony, Siemens, SBI, Motorola and Philips as its clients. Most of the software firms have agreements with the company to collect their e-waste; E-Parisaraa pays these firms for their e-waste.

Recycling of electronic waste needs to be regulated. A top-down strategy is essential for dealing with recycling of electronic waste. Policies or incentives should discourage the informal dismantling of electronic products that carry potential risks to the recycling worker's health and release of toxic pollutants in the atmosphere and to the general population. The strategy of EPR (Extended Producer Responsibility) may help recycling and remanufacturing initiatives (Lindhqvist and Lidgren 1990) EPR is a concept formally introduced in Sweden by Thomas Lindhqvist in a 1990 report to the Swedish Ministry of the Environment whose objective was to make the manufacturer of the product responsible for the entire life cycle of the product especially for the take-back, recycling, and final disposal. This means they are financially responsible for the costs of collecting, which could potentially discourage the informal dismantling of the product if a good buyback price could be availed from the manual labor of collecting, sorting, and diverting it to appropriate recycling centers.

6. ANALYSIS OF THE CASES STUDY MATERIALS IN THE CONTEXT OF DHARAVI

The study of the existing nature of the housing, living conditions, as well as the case studies of the building materials from waste lead to understand the potential factors which are important to the establishment of a circular economy of building materials from waste. Guidelines by Sumita Sinha (2012) in, *Architecture for Rapid Change and Scarce Resources*, are considered. Figure 3 summarizes the suitability of the case study materials against these criteria in blue (applicable in Dharavi) and red (unfavorable for Dharavi), respectively. The primary five factors identified are as follows: -

1) *Suitability of Use*

The needs of the local housing are based on the existing literature of Dharavi. The products need to be durable without periodic maintenance; strong, lightweight load bearing materials enabling building higher; resistant to heat transfer and water penetration; modular in nature so that

they can be manually built; and, thin to maximize usable space in resulting building.

2) *Suitability of Use in Formal Buildings*

This looks at the criterion of whether the product can find its use in the formal building market, outside of the slum, providing the local people with economic opportunities.

3) *Manufacturing Inventory needed for production*

The criterion identifies whether supplementary or new machinery are needed for production of the building material from the waste inventory.

4) *Suitability of Local Production*

This criterion indicates whether the manufacturing inventories can be installed in the work sheds of Dharavi as well as whether they can be operated by the people with minimal technical knowledge.

5) *Availability of Technical Knowledge/Research*

This criterion is based upon four sub-criteria. First, is the applicability of the case study material to the local context. Since commercial products vary from one region of the country to another, research is needed to adapt the building product to the local context. This involves identifying the specific commercial products and their material composition. Information on how to manually prepare materials for further production and when more sophisticated technological machinery is needed would be beneficial to people involved in the sorting process in Dharavi. Second is the availability of information on material characteristics like compressive strength, flexural strength, insulation value, water permeability and fire resistivity should be tested to judge the suitability of the product. Third is the scope of improvement of the product in terms of its intended performance. Fourth is the criteria of environmentally responsible, primarily concerns with safety involved in the production process as well as concerns with any toxic effects in the lifecycle of the product (for example leaching of any toxic material of a plastic product due to exposure to high temperature or ultraviolet radiation).

POSSIBLE APPLICATIONS FROM WASTE BUILDING MATERIALS **CASE STUDIES OF BUILDING MATERIALS FROM INORGANIC WASTE**

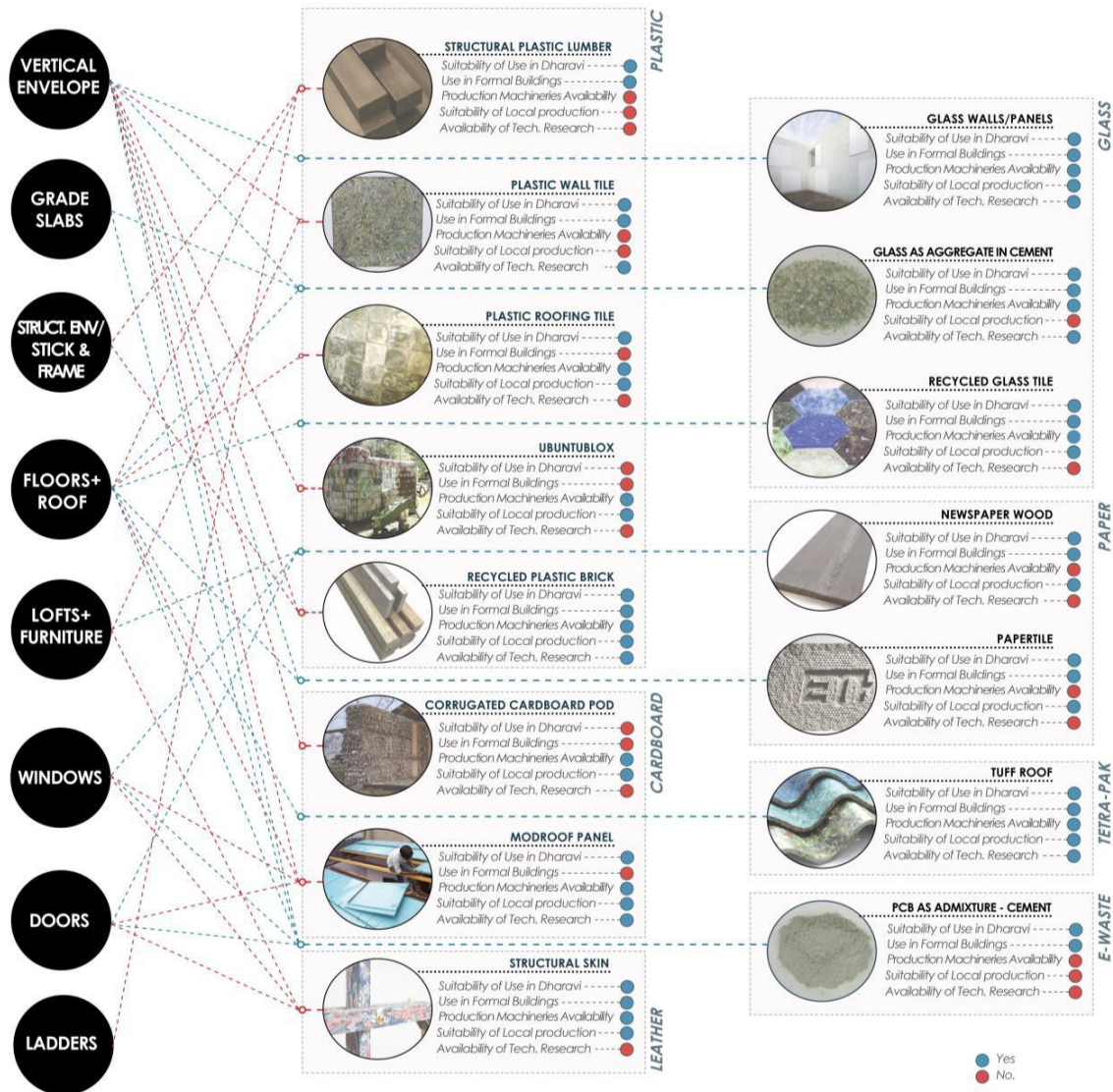


Figure 3. Summarizing the applicability and suitability of the case study building materials according the five criteria mentioned

7. CONCLUSIONS

Dharavi has an established economy of recycling, but this economy cannot be termed circular. It is a very crude model that can be improved by certain actions of the various stakeholders involved in the economy. Though it has some benefits of a circular economy, this existing economy is performed at the cost of health of the informal laborers. The existing economy has the potential to transition to a circular building economy only if the safety of the workers is taken into

consideration. This article has outlined an overview of the possibilities of a circular economy from solid waste sources focused on building materials only. Figure 3. summarizes the potential where the alternative building materials from waste mentioned in the case studies can be applied to the informal housing while Appendix A mentions in detail about the five favorability factors for each building material.

The production of most of the building materials require heavy machinery as well as technological

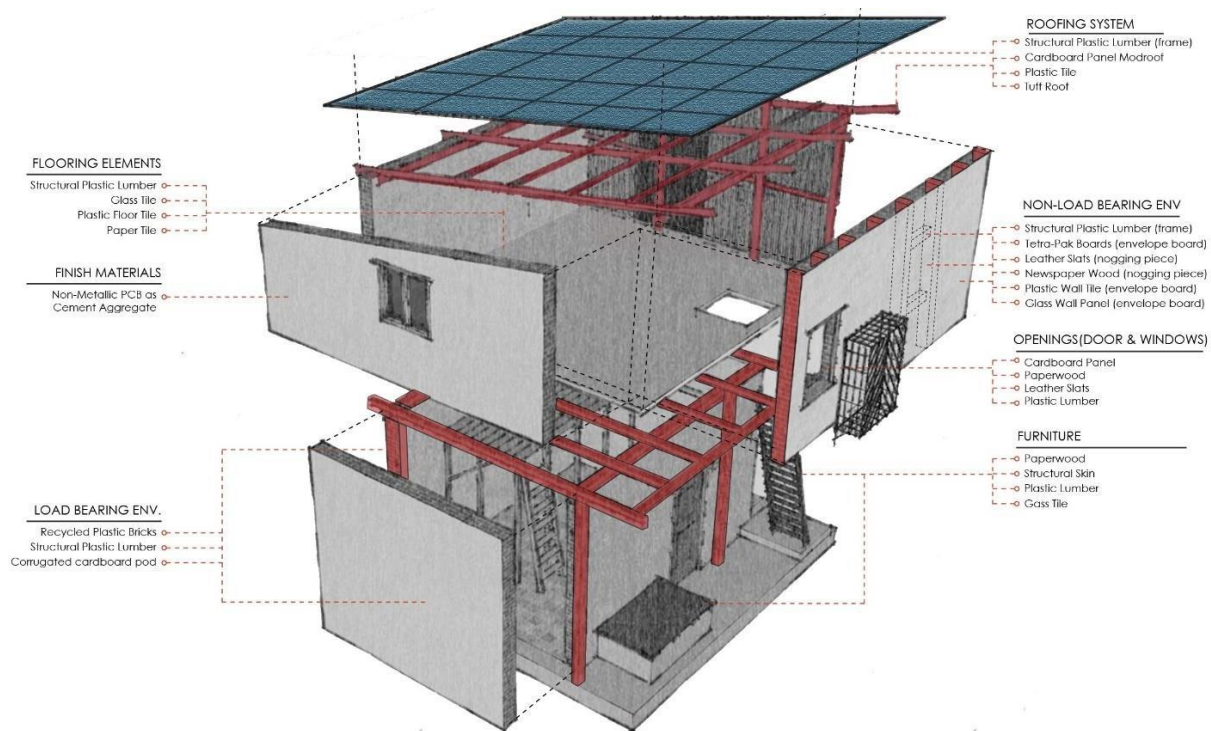


Figure 4 represents the applications of materials from waste to a building consistent with the characteristics of those found in the Dharavi slum of Mumbai

knowhow. The involvement of various non-profit organizations, the research institutes, as well as educational institutes will be necessary to identify the type of labor and financial support necessary to conduct the recycling process and to educate the people in the informal housing areas about how they can contribute to the production process. Designers also need to redesign the process so that the extraction of materials after their first use is easy and can be fed into another loop sustainably without negative impacts. With the existing waste production, research is needed to identify the consumer products and which parts of the material of the product can be recycled or extracted. Involvement of chemical and material scientists is necessary to figure out the ways to disassemble the composite materials to be further re-used identifying any potential risks associated with recycling of a product. Most of the materials will require involvement of material scientists and structural engineers to test the compressive, flexural strength, fire resistivity, durability and any long- and short-term harmful effects both in production and usage.

A concerted effort from designers, manufacturers, as well as the consumers is a necessity. Moreover, for the products to capture the market, a demonstration of the use of the products is essential both in the formal and the informal housing areas.

This article is aimed at initiating the brainstorming process required for implementation of a circular loop. It identifies the type of construction used in the informal construction, alternative building materials produced from waste, and the potential building parts that can be improved or renovated using these products. This investigation is focused more on the applicability of the waste building materials to small scale informal houses but presents an opportunity for future study of factors influencing the applicability of these materials to the formal construction market.

The article informs a potential entrepreneur or a non-profit organization about the obstacles, benefits, and the potential stakeholders to approach in order to organize the value chain of a building industry from waste providing both positive environmental and human health benefits, improved living conditions and economic gain to the inhabitants.

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References

- Al Jazeera English. 2017. *Colombia's Lego Homes*. Jun. <http://www.aljazeera.com/programmes/earthrise/2017/05/colombia-lego-homes-170531083443884.html>.
- Alternative SURFACES. n.d. *Recycled Glass Walls*. Accessed Jan 2018. <http://alternativesurfaces.net/recycled-glass-walls/>.
- Art, Royal College of. 2021. *Diana Simpson Hernandez*. 03. Accessed 2021. <https://www.rca.ac.uk/students/diana-simpson-hernandez/>.
- Bahamon, Alejandro, and María Camia Sanjinés. 2010. *Rematerial: From Waste to Architecture*.
- Baweja, Vandana. 2015. "Dharavi Redevelopment Project: Contested Architecture and Urbanism." *The Expanding Periphery and the Migrating Center: Proceedings of the 103rd Annual Meeting of the Association of Collegiate Schools of Architecture (ACSA)*. Toronto: Association of Collegiate Schools of Architecture (ACSA) Press.
- BBC News. n.d. *Life in a Slum*. Accessed 09 12, 2017. http://news.bbc.co.uk/1/shared/spl/hi/world/06/dharavi_slum/html/dharavi_slum_intro.stm.
- Benyus, Janine. 2002. *Biomimicry: Innovation Inspired by Nature*. Harper Perennial.
- Blesch, Carl, and Todd B Bates. 2016. "Recycled Plastic Lumber Invented by Pioneering Rutgers Professor." *Rutgers Today*. June 27. Accessed March 9, 2018. <https://news.rutgers.edu/feature/recycled-plastic-lumber-invented-pioneering-rutgers-professor/20160626#.WqR4dejwaUl>.
- Boano, Camillo, Jr Hunter William, and Caroline Newton. 2013. *Contested Urbanism in Dharavi: Writing and Projects for the Resilient City*. London: Development Planning Unit.
- Campana, Joseph. 2013. *Dharavi The City Within*. Harper.
- Chandran, Rina. 2016. *What's a slum? In India, Dharavi's thriving informal economy defies the label*. October 11. <https://www.reuters.com/article/us-india-landrights-slum-idUSKCN12B28D>.
- Chang, Elliot. 2013. "Inhabitat." *Glass Lab Turns Waste from Local London Businesses into Beautiful Recycled Products*. June 17. Accessed 2018. <https://inhabitat.com/glass-lab-turns-waste-from-london-businesses-and-into-beautiful-recycled-products/>.
- Day, Rani. 2010. *R[e] interpreting, imagining, developing Dharavi*. Mumbai: Society for Promotion of Area Resource Centres.
- Demir, Ismail. 2009. "Reuse of waste glass in building brick production." *Waste Management & Research*. <https://doi.org/10.1177/0734242X08096528>
- Dovey, Kim, and Richard Tomlinson. 2012. *Dharavi: Informal Settlements & Slum Upgrading*. Melbourne: Melbourne School of Design, University of Melbourne.
- Ellen MacArthur Foundation. 2016. "Circular Economy in India: Rethinking Growth for Long-Term Prosperity."
- E-Parisaraa Private Limited. 2005. *Welcome to E-Parisaraa*. Accessed March 2018. <http://ewasteindia.com/>.
- Habitat for Humanity Great Britain. 2017. *The World's Largest Slums: Dharavi, Kibera, Khayelitsha & Neza*. 12. Accessed 4 2021. <https://www.habitatforhumanity.org.uk/blog/2017/12/the-worlds-largest-slums-dharavi-kibera-khayelitsha-neza/>.
- Hebel, Dirk E., Marta H Wisniewska, and Felix Heisel. 2014. *Building from Waste: Recovered Materials in Architecture and Construction*. Birkhäuser. <https://doi.org/10.1515/9783038213758>
- Jones, Amelie. 2017. "Designer Jorge Penadés adds to pioneering portfolio with further applications of his waste leather material..." *www.we-heart.com*. May 5. Accessed March 2018. <https://www.we-heart.com/2017/05/05/jorge-penades-structural-skin-table-lamps/>.
- Lacey, Harvey. n.d. "Simple Sustainable Solutions to Empower the Impoverished around the World." *Ubuntu*. www.ubuntublox.com.

- Lindhqvist, Thomas, and Karl Lidgren. 1990. "Models for Extended Producer Responsibility."
- Materia. 2015. "Structural Skin." June 24. Accessed March 2018. <https://materia.nl/article/structural-skin/>.
- McDougall, Dan. 2007. "Waste not, want not in the £700m slum." <https://www.theguardian.com>. March 3. Accessed 09 24, 2017. <https://www.theguardian.com/environment/2007/mar/04/india.recycling>.
- Michler, Andrew. n.d. "Corrugated Fiberboard House Makes Great Use of Waste Material." www.inhabitat.com. <https://inhabitat.com/corrugated-fiberboard-house-make-great-use-of-waste-material/>.
- Morby, Alice. 2015. "Jorge Penadés creates furniture from waste leather." *Dezeen*. June 16. Accessed March 2018. <https://www.dezeen.com/2015/06/16/jorge-penades-creates-furniture-from-waste-leather/>.
- Nijman, Jan. 2010. "A Study of Space in Mumbai's Slums." *Tijdschrift Voor Economische En Sociale Geografie*. <https://doi.org/10.1111/j.1467-9663.2009.00576.x>
- Nosker, Thomas J, Jennifer K Lynch, and Lampo G Richard. 2012. *Fiber Reinforced Polymer (FRP) composites for infrastructure applications*. Springer.
- Ofori, George. 2000. "Challenges of Construction Industries in Developing Countries: Lessons from Various Countries."
- Pandey, Dr. Nisha, and Dr. Deepti Sharma. 2014. "Creating Synergy between Environment and Employment : A Case Study of Plastic Recycling Industry in Dharavi, Mumbai." *Proceedings of the Third International Conference on Global Business, Economics, Finance and Social Sciences*. Mumbai.
- Penadés, Jorge. n.d. "Structural Skin." The James Dyson Foundation. Accessed March 9, 2018. <https://www.jamesdysonaward.org/en-GB/projects/structural-skin/>.
- Razvi, Amina S. 2002. "A Multilateral Design Methodology for Development Contexts: A Framework for the Dharavi Potters." Massachusetts: Massachusetts Institute of Technology, February.
- REMATERIALS. n.d. REMATERIALS.
- Rice, Carolyn. 2017. "How recycled roofs are transforming homes in slums." *Innovators, BBC News*. Nov 21. Accessed 01 23, 2018. <http://www.bbc.com/news/business-41722794>.
- Shayna EcoUnified. 2017. "Qualities of Shayna Ecounified tiles." *YouTube*. November 14. Accessed March 10, 2018. https://www.youtube.com/watch?v=e7_9wFWa2XI.
- Sinha, Sumita. 2012. *Architecture for Rapid Change and Scarce Resources*. Routledge; 1 edition. <https://doi.org/10.4324/9780203135181>
- Smow. 2015. "DMY Berlin 2015: Structural Skin – New material by Jorge Penadés." June 12. Accessed March 2018. <https://www.smow.com/blog/2015/06/dmy-berlin-2015-structural-skin-new-material-by-jorge-penades/>.
- sP+a, and URBZ. 2015. "Reclaim Growth!" Mumbai.
- SPARC. 2013. "Incremental : A Study of Informal Incrementality, Its Impacting Factors and Supporting Systems ."
- Stahel, Walter R. 2015. *The Circular Economy — A Wealth of Flows*. Ellen MacArthur foundation.
- Temitope, AK, OO Abayomi, AO Ruth, and AP Adeola. 2015. "A Pilot Recycling of Plastic Pure Water Sachets/Bottles into Composite Floor Tiles: A Case Study from Selected Dumping Site in Ogbomoso." *Journal of Material Sciences & Engineering*, August 30.
- Tetra Pak Association. 2015. "Go Green ." June 4. Accessed 2018. <https://www.tetrapak.com/in/sustainability/our-environment-initiativ/go-green>.
- Theo, Lehner. 1998. "Integrated Recycling of Non-Ferrous Metals at Boliden Ltd." *Ronnskar Smelter*.
- United Nations Centre for Human Settlements. 1996. *An urbanizing world: Global report on human settlements 1996*. New York: Oxford University Press.
- Veit, H. M,, T. R. Diehl, A. P. Salami, J. S. Rodrigues, A. M. Bernardes, and J.A. S. Tenório. 2005. ""Utilization of Magnetic and Electrostatic Separation in the Recycling of Printed Circuit Boards Scrap." *Waste Management* 25 67-74. <https://doi.org/10.1016/j.wasman.2004.09.009>

Vyawahare, Malavika. 2017. "Can our plastic bottles and bags be turned into tiles?" *Hindustan Times*. September 29. Accessed March 10, 2018. <https://www.hindustantimes.com/environment/can-our-millions-plastic-bottles-and-bags-be-turned-into-tiles/story-b0Ut-VCIZPHBbV5z278QjBO.html>.
<https://doi.org/10.18356/42970557-en>

Wang, Ru, Tengfei Zhang, and Peiming Wang. 2012. "Waste printed circuit boards nonmetallic powder as admixture in cement mortar." *Materials ad Structures*. <https://doi.org/10.1617/s11527-012-9843-0>

Winkless, Laura. 2016. *These Houses Are Built With Blocks Made From Waste Plastic*. July. <https://www.forbes.com/sites/lauriewinkless/2016/07/21/these-houses-are-built-with-blocks-made-from-waste-plastic/#759e5ea47894>.

Yardley, Jim. 2013. "Dharavi: Self-Created Special Economic Zone for the Poor." *Deccan Herald*, June 04.

APPENDIX A - ANALYSIS OF CASE STUDY MATERIALS IN THE CONTEXT OF DHARAVI

		1. Suitability of Use in Dharavi	2. Suitability of Use in Formal Housing/Buildings	3. Manufacturing Possible with Existing Inventory	4. Suitability of Local Production in Dharavi with existing or new manufacturing inventory	5. Availability of Technological Knowledge/Research	
	Building Materials from Waste						Remarks
	<i>Plastic</i>						
01	<i>Structural Plastic Lumber</i>	✓	✓	X	X	X	<p>1. The advantages of plastic lumber are high durability, being waterproof, being bacteria-proof, low maintenance, and environmental benefits. Recycled plastic lumber have the potential to serve as the decking material for the floors of a slum house as the short span of the houses do not usually go beyond 3 to 4 meters. The plastic beams developed in (Nosker, Lynch and Richard 2012) are strong and lighter than steel, and thus plastic beams prove advantageous in terms of construction and its load bearing nature. Furthermore, they can be manually transported due to its modularity, supporting local construction techniques.</p> <p>3. Manufacturing requires installation of new machineries and not possible within any existing machineries used in other local businesses. Products can only be prepared until the processes of sorting, shredding and washing in Dharavi.</p> <p>4. Existing production methods require specialized heavy machineries in assembly line production demanding large space for installation.</p> <p>5. Technical Knowledge and research is required in terms of identifying the specific commercial plastic products in the local context which can be sorted and processed further for production. Involvement of material scientists and structural engineers are needed to develop the material from a molecular level from existing plastic products and testing is needed to understand the compressive strength, flexural strength and the fire resistivity of the product.</p>

02	Plastic Wall Tile	✓	✓	X	X	✓	<p>1. The advantages of the wall tile are that they cover less space than the brick envelope and thus provides the local people in Dharavi with more space where every inch of space matters. Additionally, they are better than the corrugated sheet metal envelope as plastic is not a good conductor of heat, and the wall tile is much more durable. The people in Dharavi are constantly repairing the houses due to poor quality materials and end up paying a significant sum over the years. The wall tile could be an improvement in terms of cost, quality, and comfort.</p> <p>3. Specialized machineries of melting, molding, and compression are used in the case study which are not available in Dharavi. Products can only be sorted, shredded and washed in Dharavi.</p> <p>4. Existing production requires specialized machineries in assembly line production demanding large space for installation.</p>
03	Plastic Roofing Tile	✓	X	✓	✓	X	<p>1. The material qualities of the tile are suited to serve as a roofing tile as they are durable, light, and waterproof. Moreover, they would not corrode, unlike corrugated metal roofing, which shows signs of corruptions over time and leaks water. There is not much information on the insulation values of the plastic tile, but this would be an improvement to the existing metal sheet used, as plastic is a poor conductor of heat</p> <p>2. Not suitable in existing urban construction but could find its applicability in the rural informal market as roofing tiles.</p> <p>3. The production of this product can be achieved locally by the people of Dharavi as it does not involve any sophisticated technologies</p> <p>5. The case study is intended to deal with low quality plastic products. Research is required to identify which commercial plastic products are suitable in the Indian context that can be locally produced in Dharavi. Testing is also required for long term effects of sun on the material, durability, check for any potential toxic leaching substances and fire resistivity of the material.</p>
04	Ubuntublox	X	X	✓	✓	✓	<p>1. Although lightweight in nature and good thermal resistant properties, it takes up too much floor space and needs steel stiffener rods that are expensive.</p> <p>2. Not suitable in the existing urban framework of urban construction but could find its potential application in rural informal settlements where availability of open</p>

							<p>space is not an issue, and the buildings need to be earthquake resistant.</p> <p>3. New business models with the support of the NGOs could examine Dharavi as the manufacturing center of the blocks, which could be transported to nearby rural areas where there is space to start up a new construction from the ground. Since this construction is good for resisting earthquakes, it could be transported to the nearby earthquake prone state of Gujarat, where the villages might find its use beneficial.</p>
05	<i>Recycled Plastic Bricks</i>	✓	✓	X	X	X	<p>1. Being lightweight and easy to build with, these recycled plastic bricks can serve as an effective replacement for the existing materials as a building skin. The fact that it can be quickly assembled and disassembled could be a good indicator of its applicability, which means that structures made of these bricks can be legally considered as impermanent structures.</p> <p>3. New machineries of compression, melting, molding and a cooling tub is needed to cool off the plastic in the mold. The material can only be prepared in Dharavi until the manual processes of sorting, shredding and washing.</p> <p>4. The machineries along with the cooling tub used in the case study for production demand large space and thus may prove to be difficult for production in the informal settlement where there is an acute shortage of space.</p> <p>5. Technical Knowledge and research is required in terms of identifying the specific commercial plastic products in the local context which can be sorted and processed further for production and the proportion of different plastics to be mixed and fed into the molding process. Other essential studies need to determine the long-term effects of heat and ultra-violet radiation on the plastic, potential toxic leaches and the fire resistivity property of the material.</p>
	Cardboard						
06	<i>Corrugated Cardboard Pod (Wax Impregnated cardboards)</i>	X	X	✓	✓	X	<p>1. Although it has high thermal mass and insulation properties. Not suitable in terms of durability, fire-resistivity, prone to be infected by insects and takes up too much space. The Corrugated Cardboard blocks have been tested to build walls from the ground. In Dharavi there is need for walls on the higher stories. Even if the cardboard blocks are used to replace the dilapidated wall of the ground floor. Making the blocks thinner would take away all the benefits gained from the blocks such as thermal mass and high insulation values, and they would be susceptible to rainwater penetration.</p>

							<p>2. It is not suitable to be used as a building product in the formal market as well. It may find its applicability as a load bearing wall for any public space in a rural urban area but would require long overhangs on top of it to protect it from rain-water damage.</p> <p>3. Although the building product has excellent structural and insulation properties research is needed to improve the durability of the product.</p>
07	<i>Modular Roof</i>	✓	✓	X	✓	✓	<p>1. The modular roof provides an ideal roofing solution in the slums of Dharavi as it complements the existing construction methods, eliminating the need for constant repairs. Furthermore, the production can be done without sophisticated technologies. This can be a viable replacement for the existing cement sheet roofing, which contains the carcinogenic material asbestos. The roof created out of the modular roofs are sturdy enough so that people can walk and sleep on them – a common activity in the slums. The modular roof has been implemented in the slums of Ahmedabad. The raw materials of cardboard and coconut waste as fiber can be easily sourced in the slum of Dharavi. This roof design provides better heat insulation, does not corrode, and provides protection from the rain.</p> <p>3. Machineries for extrusion are needed.</p>
	Glass						
08	<i>Glass Tiles</i>	✓	✓	✓	✓	X	<p>1. Can be used as floor tiles. The recycling process does not require a massive quantity of energy compared to the conventional recycling process which involves melting of the product at high temperatures.</p> <p>2. With local production and decreased cost, the tiles have a potential to be sold both in the formal and the informal market</p> <p>5. The building product is very easy to produce with manual labor nor does it involve any harm to the people as the materials are non-toxic in nature. Testing is needed to understand the compressive and flexural strength.</p>

09	<i>Glass Walls/Panels</i>	✓	✓	✓	✓	✓	<p>1. The retail shops both in and out of the slum could serve as a potential market for the building product as a low cost and durable decorative wall panel for the interior.</p> <p>2. Dharavi receives a lot of glass products in the form of glass bottles and medical vials which are of different sizes and colors. Manufacturing of the glass panels involves very low-tech technology and can be easily implemented by the people of Dharavi.</p> <p>Note: The building product is a plaster made from crushed glass applied on walls or panels.</p>
10	<i>Glass as Aggregate in Clay Brick</i>	✓	✓	✓	X	✓	<p>1. The requirement of bricks in the informal settlement would be limited to repairing any damaged brick walls on the ground floor or to improve the lightweight metal envelope of the upper floors. It has good compressive strength.</p> <p>3. Though the bricks with recycled glass additives are an improvement to the conventional bricks, the local production of the bricks with glass waste will be very polluting and thus should not be encouraged. The kiln used for clay burning for the pottery industry is itself very polluting and thus any additional industry encouraging the open burning of kilns will cause smoke pollution affecting the residents as well as the city. Thus, in Dharavi the contribution to the value chain of the industry needs to be limited to sorting the material so it can be sent to specialized cement or clay making factories.</p> <p>4. Although it is possible to make clay products in the informal settlement with the help of the heating kilns used for pottery but it is not suitable for mass production of due to space availability issues as well as pollution caused by burning of the kilns. Regulated production methods would be preferred, encouraged and supported for environmental and safety concerns.</p>
	Paper						
11	<i>Newspaper Wood</i>	✓	✓	✓	✓	X	<p>1. Newspaper wood has wood-like properties and thus it could find its applicability in making furniture in the slums, lintels for windows, and ladders and boards for the lofts. It could also be used as a decking material for the floor in place of the natural grey stone tile, provided that a reinforcement material is inserted into the material to achieve the desired flexural strength. Although suitable but the long-term durability is unknown and need to be investigated.</p>

							<p>2. Furthermore, they are suitable for local production as it does not require much technical infrastructure.</p> <p>5. Attention must be given to the chemical nature of the glue and the waterproofing coating. The glue utilized needs to be free of solvents and plasticizers to be recycled again. It's use as a sandwiched wall panel in place of the plasterboard can also be explored. For structural uses like decking material in place of wood, research and testing needs to be facilitated to understand limits of the strength of the material and its durability.</p>
12	Papertile	✓	✓	✓	✓	X	<p>1. Although suitable as a product but long-term durability is unknown and need to be investigated.</p> <p>2. It has the potential to find its application as a decorative floor tile, both in the formal and the informal market if it can give the clean smooth finish of the existing ceramic tiles by a coating of any kind of shellac or varnish material.</p> <p>3. The product is easy to make locally without sophisticated technology.</p> <p>5. Research is needed to investigate the properties of strength of the material as well on the water resistivity of the product. Attention needs to be given to the material of the organic paste used, as well as the fireproofing and the waterproofing ingredients so that they can be easily recycled at the end of the life cycle. The paper tile could also serve as a roofing tile that can span between the wooden joists of the building roof and overlap at the edges.</p>
	Leather						
13	Structural Skin	✓	✓	✓	✓	X	<p>1. The material could have potential to be used as a replacement for smaller wooden slats that are widely used in Dharavi as frames for the metal skins of the buildings. The slats may be used to make various furniture as is done by the original recycled product. There is an established leather industry whose waste would be useful for the production along with the bone glue that can also be sourced from animal bones out of the local meat shops in and around Dharavi.</p>

							5. Research is needed to understand the properties of structural strength of the material as well as its durability in terms of its response to heat, sunlight and water to understand its limits of application as a framing material.
	Tetra-Pak						
14	<i>Tuff Roof</i>	✓	X	✓	✓	✓	<p>1. The TUFF sheet would be extremely useful in Dharavi, as it is lightweight and provides suitable resistance to heat conduction compared to metal sheets. Moreover, it is a good alternative to the existing carcinogenic asbestos corrugated sheets.</p> <p>2. The tuff roof is not compatible with the formal construction techniques but is extremely suitable for the housing conditions of the rural informal settlements</p> <p>3. The Tetra Pak TUFF roof material is very suitable to fulfill the needs of the people and utilizes a common household discarded waste product. The people of Dharavi have a lot of shredding machines for the plastic industry that could be used for the Tetra Pak shredding, but they lack compression machines.</p>
	E-Waste						
15	<i>Non-Metallic PCB as Cement Aggregate</i>	✓	✓	X	X	X	<p>3. Manufacturing is not possible with existing infrastructure.</p> <p>4. The building product is made from the by-product after Printed Circuit Boards have been recycled to extract valuable metals with advanced machineries in an industrial setting. Thus, it is not possible to manufacture the product. Dharavi can only contribute to the manual labor work needed to dismantle the product, but this manual work needs to be well supervised, educated or be equipped with protective gears for the safety of the workers from the toxic elements present in the electronic waste.</p> <p>5. Research is needed to understand if the Brominated Flame Retardants (less than 2%) present in the non-metallic powder have any adverse long-term effects on human health or whether they can be extracted from the powder before using it as an admixture.</p>