Concrete block production from construction and demolition waste in Tanzania

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A B S T R A C T

In Tanzania, construction and demolition (C&D) waste is not recycled and knowledge on how it can be recycled especially into valuable products like building materials are still limited. This study aimed at investigating the possibility of recycling the C&D waste (mainly cementitious rubble) into building material in Tanzania. The building materials produced from C&D waste was concrete blocks. The concrete blocks were required to have a load bearing capacity that meets the building material standards and specifications. Eight C&D waste samples were collected from C&D building sites, transported to the recycling site, crushed, and screened (sieved) to get the required recycled aggregates. Natural aggregates were also used as control. The recycled aggregates were tested in the laboratory following the standard methods as specified in Tanzanian standards. The physical, mechanical, and chemical results showed that recycled aggregates were weaker than natural aggregates. However, chemically they were close to natural aggregates and therefore suitable for use in new concrete block production. In the production process, each experiment utilized 100% recycled aggregates for both fine and coarse portions to replace natural aggregates. The Fuller’s maximum density theory was used to determine the mix proportions of materials in which a method that specifies concrete mix by system of proportion or ratio was used. The concrete blocks production processes included batching, mixing (that was done manually to get homogeneous material), compacting and moulding by hand machine and curing in water. After 28 days of curing, the concrete blocks were tested in the laboratory on compressive strength, water absorption ratio and density. The results showed that the blocks produced with 100% recycled aggregates were weaker than those with natural aggregates. However, the results also showed that there is a possibility of recycling the C&D waste into building material because 85% of the tested concrete block specimens from recycled aggregates achieved a compressive strength of 7 N/mm2, which is defined as the minimum required load bearing capacity in Tanzania. Therefore, the C&D waste could be a potential resource for building material production for sustainable construction in Tanzania rather than discarding it. Further work should focus on the economic feasibility of production of concrete blocks with recycled aggregates in Tanzania.

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1. Introduction

Shelter is one of the basic needs of human beings. Throughout the ages, people have exploited natural resources to produce building materials to construct shelter. Even nowadays, almost all locally available building materials are derived from natural resources (Lowton, 1997). This practice continues today despite the many challenges facing current and future generations regarding the availability of building materials. The share of locally available materials used to produce building materials in Tanzania is 47% (NCC, 1992); the rest is imported, which puts significant strain on the country’s economic situation. Importation of building materials is encouraged by the Tanzanian Government, given the fact that there is a deficit of materials like cement. While building materials are already limited in many countries, their demand increases daily. In Tanzania, for example, the aggregate demand is approximated to be 2 tonnes per capita annually (Sabai et al., 2011b). The situation in other countries is 11 tonnes/ca in New Zealand, 5 tonnes/ca in the UK and 8 tonnes/ca in the US (Kirby and Gaimster, 2008). The average global aggregate demand is 3.8 tonnes/ca yearly (WBCSD, 2009). The relatively low demand in Tanzania compared to other countries may be attributed to the fact that about 80% of the population live in rural areas (URT, 2003), whereas studies show that aggregates are consumed mostly in urban rather than in rural areas (Kimambo, 1988).

It is estimated that the current population of Tanzania (approximately 43 million) will triple by the year 2050. Moreover, 75% of the population will be urban living in and around cities (PRB, 2010). This condition suggests that the dramatic growth of population will put
pressure on the provision of shelter and the availability of building materials like the predominantly used concrete blocks in the future. It is estimated that concrete blocks constitute 70% of the total building materials produced in Dar es Salaam city, Tanzania.

In addition, the construction industry is a wasteful sector: it is responsible for generating construction and demolition (C&D) waste of approximately 40–50% of the total amount of waste (Dolan et al., 1999; Macozoma, 2002; McDonald, 1996; Oikonomou, 2005). Besides the waste from normal C&D activities, other causes like war, bombing, and structural failures as well as natural disasters like, earthquakes (e.g., in Italy (2009), Haiti (2010), Chile (2010), New Zealand (2011) and Japan (2011)), avalanches, and tornadoes also contribute to the massive generation of C&D waste nowadays. Tanzania is also vulnerable to these natural (e.g., the earthquake in June, 2011) and man-made disasters like, the bomb blasts which occurred recently at Mbagala (2009) and Gongolamboto (2011) in Dar es Salaam, which left hundreds of houses demolished. Apart from the human distress, a challenging question remains regarding how to deal with this issue of a massive amount of waste.

According to Conceição Leite et al.’s (2011), one third of C&D waste generated in Sao Paulo city, Brazil is land-filled and the rest is illegally disposed. The US recycles up to 70% while The Netherlands and Germany recycle up to 90% of C&D waste generated (Conceição Leite et al., 2011). Rao et al. (2007) reported that 30% of recycled C&D waste in Taiwan is used for road construction as road base and the rest is land-filled. In most of the developing countries like Tanzania, the management of C&D waste remains a challenge because it is classified as solid waste and it is land-filled instead of being reused and/or recycled (URT, 2003, 2004). Dumping C&D waste puts pressure on acquisition of the land and its management in future. All in all, the use of C&D waste for building material production can be a good solution not only for waste management but also for providing an alternative source for building materials.

Various studies have already been carried out to find out how the C&D waste can be reused for building material production. Mueller et al. (2008) reported that the reuse/recycle of C&D waste depends on quality of constituents and the products. Bianchini et al. (2005) studied how best to reuse the recycled aggregates for concrete production. These researchers also found out that grain size fraction ranges between 0.125 and 0.600 mm of recycled aggregates can be directly re-utilized as first order material. Limbachiya et al. (2007) and Oikonomou (2005) reported that by using 30% of recycled coarse aggregates to replace natural aggregates in concrete, the products can comply with the specifications. Husken (2010) used up to 20% fine recycled aggregates to replace natural aggregates for paving block production and produced the paving blocks that fulfill the requirements given by EN 1338 on mechanical resistance and durability. Poon et al. (2002) replaced fine and coarse natural aggregates by recycled aggregates at levels varying between 25 and 100% and they found that up to 50% replacement had only little effect on the compressive strength of bricks and blocks, but above this value the compressive strength becomes unacceptable. Poon and Lam (2008) reported that they successfully used recycled materials to produce eco-friendly concrete blocks with good quality by using 100% recycled materials as aggregates: 50% recycled crushed glass (RGG) and 50% recycled crushed aggregate (RCA) together with an aggregates/cement (A/C) ratio of 4 or below. Debieb and Kenai (2008) investigated the possibility to reuse coarse and fine crushed bricks as aggregate in concrete production, and found that the level of substitution should be limited to 25% and 50% for coarse and fine crushed brick aggregates respectively. The study Poon et al. (2009) showed that the low grade recycled fine aggregates can replace natural aggregates by 50% to make non-structural pre-cast concrete blocks. These studies show that much effort has been made to recycle the C&D waste into building material particularly concrete products in different places especially in developed countries. However, in developing countries, such as Tanzania, the C&D waste is still regarded as waste to be dumped into dumping sites or thrown elsewhere, despite its recycling potential (EU Commission, 2000; Hansen, 1992; Masood et al., 2002). Knowledge on recycling cementitious rubble into building materials is still limited in developing countries like Tanzania that have limited funds and technology. This study aimed at investigating the possibility of recycling the C&D waste (mainly cementitious rubble) into concrete blocks as a material for building construction in Tanzania instead of throwing it away or using it for lower applications like infilling potholes or foundation back-filling. The rubble from construction and demolition buildings will be collected and processed to get fine and coarse aggregates which will be used in the production of concrete blocks. These concrete blocks from recycled aggregates were required to have a load-bearing capacity that meet the (local) building material standards and specifications.

The remaining sections of the paper are divided as follows: Section 2 presents the state-of-the-art of concrete block production from recycled aggregates in Tanzania. Section 3 describes materials and methods with the results presented in Section 4. The discussion of results is presented in Section 5 with conclusions in Section 6.

2. State-of-the-art of concrete block production from recycled aggregates in Tanzania

2.1. Requirements for concrete block production from recycled aggregates in Tanzania

The study was carried out in Dar es Salaam region (which comprises three municipalities, namely: Temekte, Ilala, and Kinondoni) because about 44% of construction activities are conducted in Dar es Salaam out of 29 regions in Tanzania (Sabai et al., 2011b). The search for requirements of concrete blocks with load bearing capacity as per Tanzania was first conducted. This search was carried out in order to establish the minimum material requirements that have to be met while using recycled aggregates for concrete block production with a load bearing capacity. For this purpose, the relevant stakeholders were identified and consulted. These included concrete block manufacturers, contractors and consultants, the Tanzania Bureau of Standards (TBS), research institutions – University of Dar es Salaam (UDSM), Ardhi University (ARU), National Housing and Building Research Agency (NHBRA), as well as National Construction Council (NCC), informal sectors, and clients who were represented by the National Housing Cooperation (NHC).

The Tanzanian standard for concrete blocks (TZS 283, 2002 (E)) was purchased from TBS. Structured and non-structured questionnaires were sent to 58 different building contractors, consultants, and concrete blocks manufacturers/producers out of 544 who were identified as carrying out the construction activities in Dar es Salaam city. The approximately 10% interviewed gave the representative information about how construction activities are carried out in Dar es Salaam, Tanzania. It was learnt that the materials currently used in Tanzania for concrete blocks are extracted from natural (virgin) sources and the use of recycled building materials from C&D waste is relatively new. Moreover, there is no national standard for recycled building material products. Thus, for the newly recycled concrete blocks to be accepted in the Tanzanian construction industry, they should meet the available standards which are commonly applied to the virgin materials. Information from surveyed stakeholders were used for planning the tests that were used subsequently applied to determine whether the building materials obtained from recycling C&D waste in Tanzania were of comparable quality to those produced from virgin materials as specified in the building material standards.
2.2. Building material production and testing on site in Tanzania

Investigation was carried out to determine the existing mix ratios applied in Tanzania. It was found that the mixing ratios for concrete block production differ from one producer to another depending on various individual factors such as demand of clients, planned selling price, and decision of the producer. It was discovered that one cement bag can produce 26–60 concrete blocks depending on the mix ratio and targeted customers. Interviewees noted that the mix ratio is confidential information as far as trade is concerned. The mix ratio is established at the building site, depending on experience, just by counting the number of shovel/spade, basins (kara), buckets, or wheel barrows full of the required material. The cement–aggregate mixing ratios applied, according to field survey, are estimated to range from 1:7 (1/7) to 1:14 (1/14) by volume. After deciding on the mix ratio, the conventional concrete block production processes such as mixing, compaction, and moulding, is applied. Subsequently, blocks are cured by sprinkling with water for 3–7 days. In the days after the blocks are cured by air.

Next, quality assurance testing is performed. The survey showed that out of 58 respondents, only about 20% of the building contractors test the quality of their material products in the laboratory. The main reasons why a laboratory is not used for testing were lack of equipments and limited funds. This implies also that there is lack of enforcement of regulations and technical personnel. The main concrete block parameters tested are compressive strength and density. However, most of them do not test in the laboratory. About 80% of them use simple tests on site. The first method reportedly used is lifting up and dropping the concrete block down to the ground. The expected outcome of this experiment is that the block will break into two pieces only if it is strong. But if it disintegrates into more pieces, it is disqualified. The second test is done by scratching the surface of the block using one’s fingers; if it erodes easily, it is disqualified. The third test is cutting the block using an axe; if it breaks easily, it is disqualified. These methods are not reliable because they depend on factors that cannot be controlled. Laboratory testing and analysis are required for quality control to ensure the quality of the concrete products especially those produced using recycled C&D waste.

Those contractors who do test the quality of their products do so at the Laboratory of the Tanzania Bureau of Standards (TBS) and/or at the University of Dar es Salaam Building Materials laboratory. The survey findings (see Table 1) showed that the compressive strength produced ranges from 2.1 to 11.6 N/mm² (MPa). According to Tanzanian standards (TZS 283, 2002 (E)), the recommended compressive strength ranges from 3.5 to 21 N/mm². Through it does not specify the type of building that the products may be used for. Even though not categorized based on load bearing and non-load bearing compressive strength, the contractors and consultants who were interviewed indicated that they categorize concrete blocks with load bearing block as the ones which have a minimum compressive strength of 7 N/mm². This value is also reported by Poon et al. (2002), Neville (1995), and Jackson and Dhir (1988). Concrete blocks with compressive strength below 7 N/mm² are mostly used as a structural material for single-storey low-cost houses in Tanzania. However, Neville (1995) recommended that the concrete blocks with compressive strength less than 7 N/mm² can be used for non-structural purposes. In this study, the concrete blocks with load bearing capacity are defined as those concrete blocks that achieved the minimum compressive strength of 7 N/mm². Recycled aggregates from C&D waste aimed to be used to replace natural aggregates to produce the concrete blocks that meets the required standards and specifications as specified in Tanzanian standards, i.e., TZS 283, 2002 (E). Furthermore, all the recycled concrete block specimens in this study were tested in the laboratory to determine their quality.

3. Materials and methods

3.1. Materials

3.1.1. Materials and sampling

The aggregates used in this study for the production of concrete blocks were derived from C&D waste from building construction and demolition sites in Dar es Salaam, Tanzania. Stratified random sampling (Kothari, 2004) was used to select C&D waste sources in Dar es Salaam city. Dar es Salaam city is made up of three municipalities, namely Tememe, Kinondoni, and Ilala. In order to get representative data, the C&D waste materials for concrete block production were sampled from all three municipalities. The three municipalities share most of the main building material sources like quarries for aggregates. Therefore, the quality of recovered waste might not be affected by spatial distribution of the sources of natural materials. However, it was assumed that the demolition waste might be weaker than the construction waste due to the fact that demolition waste existed longer and its quality may be degraded. Therefore, demolition waste deserved more attention. For this reason, more samples were collected from demolition waste than from construction waste. These samples consisted of 60% demolition waste, 20% construction waste, and 20% natural sources as control. Both demolition and construction waste samples were obtained from single- and multi-storey buildings in equal amounts in order to have a good representation of C&D waste that is generated in Tanzania. In this paper, the abbreviations used for the different types of waste are as follows: DM1, DM2, and DM3 standing for demolished single-storey buildings; DS1, DS2, and DS3 for single-storey demolished buildings; while CM and CS stand for multi-storey and single-storey construction buildings, respectively. Each C&D waste sample produced both fine and coarse aggregates that were used for concrete block production with the respective sample in this study. In addition, NCA and NFA stand for natural coarse aggregate (gravel) and natural fine aggregates (sand) from natural (virgin) resource respectively. The natural aggregates were used for control purpose. Other materials used include cement and water.

3.1.2. Composition of C&D waste in Tanzania

The composition of C&D waste used to produce the recycled aggregates in Tanzania was obtained by first mixing the C&D waste from both single and multi-storey buildings. Waste from both single and multi-storey buildings were used because, in Tanzania, the
building materials used in construction for these buildings differ in terms of their quality. For example, most of multi-storey buildings are framed structures while, single-storey buildings are wall structures. Subsequently, the heap of C&D waste was reduced by quartering (see Fig. 1b) from approximately 1000 kg to 250 kg and then sorted. After sorting, the mass of concrete and cementitious rubble was weighed using Golden Mark (100 ± 0.5 kg). Similarly, glass, wool, wood, and metal present were measured using digital balance SMS. The composition results are presented in Table 2. As seen from the table, the recycled C&D waste was used mainly (i.e., 99.88%) cementitious rubble.

3.2. Material processing and volume reduction for laboratory analysis

The C&D waste was crushed to produce both fine and coarse aggregates for concrete block production. The heaps of rubble were manually crushed using hammers (Fig. 1a) to get the recycled aggregates. Unwanted waste portions like metals, wood, plastics, gypsum, and papers were removed manually during the crushing and screening process. In the next step, 50 kg of aggregates were sampled from each recycled aggregates sample (heap). In order to collect a representative sample, the quartering method was applied as recommended in the standard methods (TZS 58, Parts 1–3, 1980) and as shown in Fig. 1b and c. Next, the reduced sample (50 kg) was sent to the University of Dar es Salaam (Building Material Laboratory) for testing. In the laboratory, the 50 kg sample was further reduced by a sample divider (Fig. 1c) to the required amount of materials for a particular test.

3.3. Aggregate characteristics

3.3.1. Physical and mechanical analysis

Recycled aggregates and aggregates from natural resources may differ in terms of quality which may have an impact on the quality of the product (Mueller et al., 2008). In order to understand the quality of the recycled aggregates generated in Tanzania, the physical, chemical–mineralogical, and mechanical properties of the samples were analyzed in the laboratory. The physical and mechanical parameters tested included grading (particle size distribution), crushing strength value, 10% fines values, density, water absorption ratio, organic impurities, and pH. All these tests were carried out according to standards methods (TZS 58 (Parts 1–3), 1980). Two replicate tests were carried out for each test and averaged to obtain the results herein presented.

3.3.2. Chemical analysis

In this study, all eight recycled and two natural aggregate samples were chemically analyzed. The chemical–mineralogical composition of the C&D waste samples was determined by using X-ray diffraction (XRD), X-ray fluorescence (XRF) spectroscopy, and scanning electron microscope (SEM) techniques. All samples were prepared into powder form. The analysis instruments used were an automated X-ray fluorescence analyzer (ARL 9400), Rigaku and high resolution SEM JEOL 7500 FA. The results of this analysis are presented in Section 4.1.2.

3.4. Characterizing cement and water

In this study, Portland–composite cement (Cem II/A-L/32.5R) from Tanzania Portland Cement Company (TPCC) was used. The chemical–mineralogical characteristics of the cement were determined using analytical techniques such as XRF, XRD, and SEM. The density of the cement was also determined. The Pycnometer method using Micromeritics Accupyc II 1340 was used for density measurement whereby 12 measurements were carried out, and particle size distribution was also measured with a Mastersizer 2000 instrument according to ISO 13320-1, 1999. Also, the quality of water used for the mixing and curing processes was tested in the laboratory to determine the level of impurities which may impair the strength or durability of the concrete blocks (TZS 283, 2002 (E)).

3.5. The concrete block production processes

The concrete block production process starts when materials are acquired and continues until the concrete block has been produced, tested, and found fit for building construction. This section outlines the procedures that were followed in this study to produce the concrete blocks from recycled aggregates as illustrated in Fig. 2 and in the detailed descriptions that follow.

From Fig. 2, the terms used were defined as follows:

i. Resource input: the resource input includes materials such as concrete and masonry rubble, natural aggregates, water, and cement. Other inputs were labour, energy, and information. Energy inputs are negligible, since most processes were carried out manually. Information includes guidelines for the concrete block production process (e.g., the required curing time), concrete block specifications, and standards. In this study, the focus was on concrete blocks with a load bearing capacity produced from recycled C&D waste after 28 days of curing. The required
load bearing capacity in Tanzania for concrete blocks is set at a minimum strength of 7 N/mm² (Jackson and Dhir, 1988; Neville, 1995; Sabai et al., 2011b; TZS 283, 2002 (E)).

ii. Determination of mix proportions (parameters): the method for determining the mix parameters used in this study is the same as that normally used in UK according to Teychenne et al. (1997) which specifies concrete by system of ratios. Normally, this method applies Fuller’s maximum density method. According to Raju (2002), Fuller advocates the maximum density theory which states that the greater the amount of solid particles that can be packed in a given volume of concrete, the higher the strength. Fuller’s ideal grading curve for maximum compaction is based on Eq. (1) (Husken, 2010; Raju, 2002). The dense packing is facilitated by the fact that holes of the large particles are filled with small particles whose voids in turn are filled with smaller ones and so on to the smallest diameter (Brouwers, 2006). According to Husken (2010) and Schoner and Mwita (1987), Fuller’s method is the one which is adopted in most of the design codes for normal concrete strength. Since the focus of this paper is to explore whether the recycled aggregates can produce building materials following Tanzanian practices, the mix ratio method was applied. According to Schoner et al. (1987), the mix ratio for concrete blocks production in Tanzania is specified as 1:9 being the proportion of cement to aggregates by volume. Then by applying an analytical method of combining aggregates (Raju, 2002; Schoner and Mwita, 1987), the fine and coarse aggregates fractions were estimated. Out of nine parts of aggregates, the fine:coarse aggregates ratio obtained was 5:4. This shows that the cement-aggregates ratio used was 1:5:4 (cement: fine (sand):gravel parts in volume). This ratio is equivalent to 1:4:3.3 parts in weight, respectively. The fine aggregates used were those that passed through 5 mm sieve size and coarse aggregates ranging from 5 mm to 12 mm (GTZ, 1991; Jackson and Dhir, 1988). The water/cement ratio used ranged from 0.58 to 0.75 (by weight) that was obtained through trial mixes. These values were higher compared to Tanzanian practices which range from 0.23 to 0.30 (by weight) as reported by Building Material Engineers from UDSM building material laboratory. The difference from the one normally applied in Tanzania may be caused by the nature of the material used (i.e., recycled aggregates, which are more porous than the natural aggregates)

\[ p = 100 \left( \frac{d}{D} \right)^{1/2} \]  

where \( p \) = percentage of material smaller than “d (mm)”; \( D \) = maximum particle density (mm).

iii. Concrete block fabrication: after determining mix proportions and the compaction method as well as having the equipment, the conventional production processes of concrete blocks were adopted. These processes include batching, mixing, compacting, moulding, and curing. Fresh concrete with slump less than 10 mm was prepared manually until a homogenous mixture was obtained as shown in Fig. 3 in order to get stiff concrete. The manual compaction machine was used. The method is cheap, easy to apply, and the one commonly used by concrete block producers in Tanzania. Of course, the method is not as

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**Fig. 2.** Concrete block production from recycled aggregates flow-chart.

**Fig. 3.** Mixed materials, compaction technique and moulding machine used for concrete block production.
3.6. Testing of concrete

3.6.1. Testing of fresh concrete

Slump test was used to analyze characteristics of fresh concrete of recycled aggregates. The slump test was carried out following standard method described in TZS 62 (Part 2), 1980.

3.6.2. Testing of hardened concrete block specimens

After the 28 days of curing, the concrete block specimens were taken to the laboratory at the University of Dar es Salaam for testing. The density, water absorption ratio, and compressive strength were tested. The analysis was carried out according to the standard methods which are specified in the NEN-EN 772-1, 2000, TZS 283, 2002 (E) and TZZ 58 (Part 3) 1980. The following is a summary of how the analysis was carried out.

(1) Compressive strength test: The concrete block specimen was placed and centred on the plate of a compression testing machine. The compaction machine (MFIL System PRUF UND MESS) with a maximum of 3000 kN was used. The gross area of the loaded surface was length × width, i.e., 450 × 230 (mm) bed face according to NEN-EN 772-1, 2000 and TZZ 283, 2002 (E). Two soft sheets of plywood were placed under and above the specimen to reduce friction. Poon et al. (2009) also applied the same technique on compressive strength testing. To calculate the compressive strength, Eq. (2) was used. The compressive strength result reported is an average over five specimens.

\[ f_c = \frac{1}{n} \sum_{i=1}^{n} \frac{F}{l \times w} \]

where \( f_c \) = compressive strength, N/mm²; \( F \) = failure load in N; \( l \times w \) = area of base-face, mm²; \( l \) = length and \( w \) = width of the block.

Mean strength and standard deviation for the 45 concrete block specimens were analyzed as well.

(2) Density: Concrete block specimens were weighed by SOEHNLIN-Wagebereich 0.5 bis 55 kg and the dimensions were measured by vernier calliper with 50 cm and 100 divisions. The density was calculated using Eq. (3). For each sample type, the average of the five specimens was calculated:

\[ \rho_b = \frac{M}{l \times w \times h} \]

where \( \rho_b \) = density of the block, kg/m³; \( M \) = mass of the block, kg; \( l \times w \times h \) = volume of the block, m³; \( l \) = length, \( w \) = width and \( h \) = height of the block, m.

(3) Water absorption ratio: The wire basket method was used for water absorption analysis for aggregates larger than 10 mm size (TZS 58 (Part 3), 1980). Even though the standard method described in TZS 58 (Part 3), 1980 was for aggregates, it can also be used for other solid materials like concrete blocks. Since it was not possible to measure the whole concrete block, the size was reduced by cutting the concrete blocks into small pieces with each one having almost one-eighth of the size of a concrete block. Two specimens were tested for each concrete block sample. The water absorption ratio was calculated by using Eq. (4) and the average result of the two specimens was calculated.

\[ W_{ab} = \frac{A - D}{D} \times 100\% \]

where \( W_{ab} \) = water absorption, %; \( A \) = weight of the surface dry saturated concrete blocks, kg; and \( D \) = weight of oven dry concrete blocks, kg.

4. Results

4.1. Characteristics of recycled aggregates in Tanzania

4.1.1. Physical and mechanical characteristics of recycled aggregates

The results of the physical and mechanical characteristics for both recycled and natural aggregates are presented in Table 3, Figs. 4 and 5.

In Fig. 4, the results show that the grading curves of DS1, DS2, CS and DM2 were above the ideal curve which implies that more cement and/or compaction is needed in order to achieve the maximum density, which will result in greater strength of concrete product. The loads applied for 10% fines value (TFV) were varied as 400 kN, 100 kN, and 50 kN in order to use the graphical approach to estimate the TFV. The results of TFV are shown in Fig. 5. The results from Fig. 5 show that the load required to produce 10% fines were out of range for all recycled aggregates except for construction waste delivered from multi-storey buildings (CM) and natural
Aggregates for which 10% fines values were obtained when 130 kN load was applied.

4.1.2. Chemical–mineralogical of recycled aggregates

According to X-ray diffraction analysis, the main identified phases in all materials were SiO₂, CaCO₃, Ca(OH)₂, and various calcium aluminosilicates as shown in Fig. 6. In Fig. 6, the C&D waste samples from single storey buildings were close to natural sand (NFA) whereas the C&D waste samples from multiples from multi-storey buildings were close to natural gravel (NCA).

Scanning electron microscopy (SEM) was also used to detect the chemical elements present in the recycled aggregates. An EDX detector coupled to a FEI Quanta 600 F E-SEM was used. The chemical elements found in all samples were C, O, Ca, Al and Si. The XRF results are presented in Table 4. In Table 4, almost all C&D waste samples were mainly composed of SiO₂ like natural sand (NFA). However, physical observation showed that the recycled concrete rubble was composed of limestone-like (CaCO₃) NCA as coarse aggregates. These results suggest that the either origin rubble was dominated with sand (fine aggregates) and/or less cement was used in concrete mix.

4.2. Characteristics of cement and water used for concrete block production

The density and particle size distribution (PSD) of the Portland-composite cement (PCC) were analyzed according to standard methods (ISO 13320) as described in Section 3.4. The results for 12 measurements were relatively close to each other and the average density was 3.01 g/ml. The PSD result is presented in Fig. 7. Also, before commencing concrete blocks production, the water was tested and the results are shown in Table 5. The results of the chemical composition of cement (i.e., CEM II/A-L32.5R) in Tanzania showed that it is mainly composed of C, O, Si, Al, Mg, Fe, Na, S elements, and the chemical oxides presented in Table 6. The chemical composition of cement used complied with the Tanzanian standard (TZS 727 (Part 1), 2002) because the ratio of CaO/SiO₂ by mass was not less than 2.0 and content of MgO was less than 5.0%.

Table 3

Physical and mechanical characteristics of recycled aggregates in Tanzania.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gross density (g/cm³)</th>
<th>Water absorption (%)</th>
<th>pH</th>
<th>Aggregate crushing strength value (%)</th>
<th>Organic impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS1</td>
<td>2.5</td>
<td>2.2</td>
<td>10.3</td>
<td>9.7</td>
<td>58.5</td>
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<td>DS2</td>
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<td>2.2</td>
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<td>71.5</td>
</tr>
<tr>
<td>DS3</td>
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<td>2.2</td>
<td>8.1</td>
<td>11.0</td>
<td>47.9</td>
</tr>
<tr>
<td>DM1</td>
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<td>2.1</td>
<td>5.6</td>
<td>11.1</td>
<td>38.2</td>
</tr>
<tr>
<td>DM2</td>
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<td>2.2</td>
<td>10.7</td>
<td>8.8</td>
<td>57.8</td>
</tr>
<tr>
<td>DM3</td>
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<td>7.6</td>
<td>9.4</td>
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</tr>
<tr>
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<td>9.1</td>
<td>9.6</td>
<td>49.3</td>
</tr>
<tr>
<td>CM</td>
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<td>2.3</td>
<td>6.2</td>
<td>11.5</td>
<td>30.4</td>
</tr>
<tr>
<td>NCA</td>
<td>na</td>
<td>2.4</td>
<td>1.8</td>
<td>8.8</td>
<td>28.6</td>
</tr>
<tr>
<td>NFA</td>
<td>2.5</td>
<td>na</td>
<td>na</td>
<td>8.8</td>
<td>na</td>
</tr>
</tbody>
</table>

*na* means not applicable because analysis requiring either fine or coarse aggregates.

Fig. 6. X-ray diffractograms of the NFA, CS, DS1, DS2, DS3, NCA, CM, DM1, DM2 and DM3 aggregate samples; (●) SiO₂, (▲) CaCO₃, (■) Ca(OH)₂, (♦) C-A-S.

Adapted from Sabai et al. (2011a).

Fig. 7. PSD of Portland composite cement of TPCC, Tanzania.
Table 4
XRF chemical composition of recycled C&D waste and natural aggregates used in Tanzania.

<table>
<thead>
<tr>
<th>C&amp;D waste samples</th>
<th>Natural (virgin) sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS1</td>
</tr>
<tr>
<td>Major elements (% weight)</td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>71.81</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.60</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.25</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.45</td>
</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
<td>15.43</td>
</tr>
<tr>
<td>MgO</td>
<td>0.23</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.17</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.26</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.02</td>
</tr>
<tr>
<td>Trace elements (ppm)</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>41.3</td>
</tr>
<tr>
<td>Ni</td>
<td>51.8</td>
</tr>
<tr>
<td>Sr</td>
<td>238.2</td>
</tr>
<tr>
<td>Ba</td>
<td>124.4</td>
</tr>
<tr>
<td>Zr</td>
<td>272.4</td>
</tr>
</tbody>
</table>

<" means less than detection limit.

4.3. Fresh concrete

The slump test results ranged from 5 mm to 10 mm. According to TZS 62 (Part 2), 1980, fresh concrete with slump less than 10 mm has a stiffer consistency. Hence, the fresh concrete for concrete block production was stiff as shown in Fig. 3 (mixed material).

4.4. Concrete block results

The concrete blocks were produced by using both fine and coarse aggregates from the same sample of recycled aggregates except for natural aggregates where sand and gravel were used together as is normally done in Tanzania. After 28 days of controlled conditions of curing, the concrete blocks were taken to the laboratory for testing. The compressive strength, water absorption ratio, and density were measured and the results are shown in Fig. 8. The results showed that the compressive strength of recycled aggregates ranged from 5.2 to 10.4 N/mm² but was 14.2 N/mm² for natural aggregates. Moreover, a mean compressive strength of 8.8 N/mm² with a standard deviation of 2.1 N/mm² was obtained for concrete block specimens produced from recycled aggregates. On the other hand, a mean compressive strength of 9.4 N/mm² with standard deviation of 2.6 N/mm² was obtained for concrete block specimens produced from recycled aggregates and natural aggregates. This corresponds to a minimum strength of 6.7 N/mm² and 6.8 N/mm² for those concrete blocks produced using only recycled aggregates and those from a combination of recycled and natural aggregates respectively. The results indicate that all samples have a compressive strength higher than 3.5 N/mm² according to TZS 283, 2002 (E) but, only 85% of the specimens achieved the 7 N/mm² standards (for load bearing capacity in Tanzania).

Table 6
XRF chemical composition of cement.

<table>
<thead>
<tr>
<th></th>
<th>Main elements (% weight)</th>
<th>Trace elements (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td></td>
<td>19.93</td>
<td>5.99</td>
</tr>
</tbody>
</table>
5. Discussions

5.1. Aggregate quality

Results for aggregate characteristics as presented in Table 3, Figs. 4 and 5 in Section 4.1 indicate that the recycled aggregates were less dense than natural aggregates. In addition, the fine aggregates were denser than coarse aggregates for both recycled and natural aggregates. However, the grading results in Fig. 4 show that curves for CM, DM1, DM3, DS3, and natural aggregates (NCA) comply with Fuller’s ideal curve; on other hand, the DS1, DS2, CS, and DM2 grading curves did not. These results suggest that the use of more fine aggregates and high compaction mechanism may be needed for the DS1, DS2, CS, and DM2 samples in order to produce concrete blocks with high strength. The concept for using more fine aggregates to fill voids of coarse aggregates in production of concrete with high strength is supported by particle packing concepts in paving block production as reported by Husken (2010).

The results of aggregates crushing values (ACV) as presented in Table 3 also show that aggregates crushing value (ACV) for recycled aggregates ranged from 30.4% to 71.5% compared to natural aggregates ACV of 28.6%. According to TZS 58 (Part 2), 1980, the maximum recommended crushing value for aggregates to be used for concrete and wearing surfaces are 45% and 30%, respectively. This indicates that no recycled aggregates qualify to be used for wearing surfaces except natural aggregate with crushing strength value of 28.6%. Only crushing strength values of DM1 (38.2%) and CM (30.4%) met the specification which is required for concrete for all recycled aggregates. This indicates that about 75% of the recycled aggregate samples failed to achieve the recommended standards (TZS 58 (Part 2), 1980). Poon et al. (2002) reported that the recycled aggregates crushing strength value in Hong Kong ranges from 21.6% to 24.5%. This shows that recycled aggregates from Hong Kong are stronger than those from Tanzania, and their recycling techniques might vary depending on initial quality of the recovered waste to be recycled. This condition suggests that it is impractical to directly transfer outcomes from one country to another especially those where the levels of technology differ significantly (e.g., Hong Kong and Tanzania).

In addition, the 10% fines values (TFV) were tested and the results are presented in Fig. 5. The results show that the TFV for CM and NCA are obtained by applying 130 kN. For the rest of the recycled aggregates, the results showed that the TFV is out of range even though, the graphs of percentage of materials passing through the 2.36 mm sieve size versus load applied gave high value with correlation coefficient (R²) which were greater than 93%. Unlike Poon et al. (2009) and Poon et al. (2002) who indicated that the TFV of recycled aggregates ranged from 72 to 145.1 kN, in this study, the TFV obtained from recycled aggregates from construction waste, and the rest of the recycled aggregates were out of range. The TFV results indicate that the recycled aggregates from demolition (i.e., DSs & DMs) waste and construction waste from single-storey building (CS) in Tanzania are very weak. This condition may be caused by low cement content applied in the old concrete rubble or because the rubble was dominated mostly by mortar (cement-sand) materials.

The water absorption ratio results (Table 3) ranged from 6.2 to 13% for the recycled aggregates while for natural aggregates it was 1.8%. The results suggest that the recycled aggregates were porous about 7 times (700%) more porous than natural aggregates. Our results are generally in agreement, even relatively higher, than previous studies conducted in Hong Kong where it was reported that water absorption for recycled coarse aggregates ranged from 4.2 to 7.6% (Poon et al., 2002, 2009). This could be caused by the presence of the cement paste/mortar attached to the crushed recycled aggregates.

The pH of both recycled and natural aggregates was above 7. This reveals that all aggregates are basic in nature. However, the pH of the recycled aggregates from construction waste (CM) had higher pH value than the others. This could be attributed to their origins. For example, the aggregates recovered from CM originated from granite rock while the rest were limestone (calcium carbonate). Since limestone is composed of carbonates its pH may be lowered when it gets in contact with water.

The results for organic impurities that are presented in Table 3 indicate that almost all recycled aggregates are polluted except the recycled aggregates from construction waste (CM) and natural sand (NFA). The CM sample was not organically polluted due to the fact that the CM sample was mostly composed of residual concrete and broken blocks while other recycled aggregates were sampled and sorted from mixed debris. This indicates that re-utilization of C&D waste as a material input for concrete blocks production will reduce not only the shortage of building materials, but also the environmental burdens. Consequently, C&D waste recycling will contribute safeguarding people’s health while achieving sustainable construction in Tanzania.

Results in Table 4 of recycled aggregates (DSs, DMs, CM and CS) are in firm agreement with results of recycled aggregates as presented by Limbachiya et al. (2007) for both in percentage (%) weight (for main elements) and ppm (for trace elements) regardless of their difference in locations of origins. These results suggest that the chemical composition of C&D waste may be similar in geographical locations. However, the physical and mechanical characteristics may differ depending on the original concrete mix used and the targeted quality of the concrete products, which mostly are influenced by the available technologies and the economic status of the respective country.

The CM as well as DM1, DM2 and DM3 samples seem to be closer in chemical–mineralogical composition to NCA (natural coarse aggregates) while the rest of the recycled aggregates of single-storey buildings are more similar to NFA (natural sand). These results suggest that the original concrete mix of rubble particularly from single-storey buildings was mainly composed of sandy material and/or less cement material. Based on results of C&D waste composition in Table 2, the concrete, which also contains cement–sand matrix like mortar comprises about 39% of C&D waste recycled in Tanzania; the rest is almost cement–sand matrix waste. These results suggest that the original rubble was dominated with sandy materials (fine aggregates) and/or less cement was used in the concrete mix. These results indicate that the original concrete mixtures were mostly composed of sand (i.e., 60% (see Table 2)) and less cement (e.g., 1:14 (see Table 1)). This could be one of the reasons why concrete blocks having compressive strength as low as 2.1 N/mm² are produced in Tanzania.

5.2. Cement and water

The results in Fig. 7 and Table 3 showed that cement and water used in concrete block production in Tanzania were within the minimum requirements specified in TZS 727, 2002 (CEM II/A-1/32.5) and TZS 789, 2003, respectively. Thus, they had no impact on the strength of the concrete blocks.

5.3. Concrete blocks from recycled C&D waste

The results presented in Fig. 7 show that the denser the concrete blocks (i.e., the higher the density value), the higher the value of compressive strength. For example, concrete blocks with densities more than 1900 kg/m³ had a compressive strength of more than 7 MPa while DS3 that had lower density value than others, also had a lower compressive strength (5.2 MPa). These results are generally in agreement with Fuller’s theory that the higher the
density, the higher the strength (Raju, 2002). However, the compressive strength results of DS3 pose a challenge because the results of aggregates grading corresponded to the ideal curve. Furthermore, ACV analysis results showed that DS3 had lower value (49.1%) compared to DS1 (58.5%), DS2 (71.5%), DM2 (57.8%), and CS (49.3%). This outcome may be affected by the compaction technique (manual) which was used because the water absorption ratios showed that DS3 had a higher value of 15.1% compared to, for example, that of the CS (8.6%), DM2 (8.8%), DS1 (12.3%). Since it was manual work, maybe a worker was tired at the end of the day.

In this study, manual technology was used in production of concrete blocks from C&D waste because it is affordable to many Tanzanians due to limited funds in many developing countries. Regardless of manual technology, the average compressive strength of the 58 concrete blocks specimens, produced from C&D waste, that were tested was 8.8 N/mm². Tanzanian Standards (i.e., T25 283, 2002 (E)) allows concrete blocks with compressive strength of 3.5 N/mm² to be applied in construction industry in Tanzania. This suggests that there is a possibility for developing countries like Tanzania to recycle C&D waste into building materials instead of throwing them away.

Furthermore, the compressive strength results indicate that there is a possibility to recycle the C&D waste into load bearing concrete blocks because approximately 85% of concrete blocks specimens tested in the laboratory attained compressive strength of more than 7 N/mm². The recycling of C&D waste into building materials could help to solve the problems of solid waste disposal in Tanzania as well as become an alternative resource for production of new building materials and therefore, contribute to conserving natural resources, increasing employment, and improving the economy of the nation at large.

6. Conclusions

The aim of this paper was to investigate the possibility of recycling the C&D waste (mainly cementations rubble) into concrete blocks as a material for building construction in Tanzania instead of throwing it away or using it for lower applications like infilling potholes or foundation backfilling. The rubble from construction and demolition buildings were collected and processed to get fine and coarse aggregates which were used in the production of concrete blocks. In this research, the recycled aggregates for both fine and coarse samples replaced natural aggregates by 100% in the concrete block production. The recycled aggregates were tested to understand their physical, chemical, and mechanical characteristics, and the results were subsequently applied in mix design for concrete block production.

The recycled aggregates in Tanzania were found to be weaker in terms of strength than those produced with natural aggregates as well as those produced in Hong Kong. The poor (weaker) condition of recycled aggregates in Tanzania compared to those from Hong Kong suggests that the cement content of the old concrete waste was poor as well. For example, current concrete blocks are produced in Tanzania from natural (virgin) aggregates having relatively low compressive strength of 2.1 N/mm². These conditions are likely to affect the quality of the concrete block to be produced from them. Also, high percentage of water absorption suggests that the recycled material is composed mostly of cement paste materials, i.e., mortar (sand–cement) than stone materials. On other hand, chemical–mineralogical results indicated that the recycled aggregates from building construction and demolition waste in Tanzania have no inorganic contaminants which can affect the building materials produced from these aggregates, and therefore, they are suitable for use in new concrete block production. Furthermore, the similarities in chemical–mineralogical composition between recycled aggregates and those from natural sources indicate that there is less cement used in origin concrete waste. Based on these findings, further studies are required to identify kind of organic impurities present in the C&D waste in Tanzania and how that can affect the recycled product.

In this paper, the concrete block production technology used was manual which is mostly applied and affordable to many concrete block producers in Tanzania. A hand (manual) machine was used for compacting and moulding processes. After 28 days of curing, the concrete blocks were tested in the laboratory. This technology was capable of producing concrete blocks with load bearing capacity and a compressive strength of at least 7 N/mm² from 89% of C&D waste samples recycled and 85% of specimens tested. These results indicate that there is a possibility to recycle C&D waste in building material production in Tanzania regardless of existing technological challenges. The C&D waste recycling will result in improved social, economical, and environmental welfare in terms of creating more employment, reducing health hazards caused by C&D waste disposal, reducing the cost of waste management and providing an alternative source of building materials in Tanzania. As a result, natural resources will be conserved for future use and the construction industry in Tanzania will become more sustainable. Further work should focus on investigating the technology that is capable to produce the minimum compressive strength of 7 N/mm² for all (100%) C&D waste samples recycled. Other area of further study will be a detailed economic feasibility of the production of concrete blocks with recycled aggregates in Tanzania.

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