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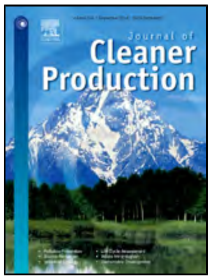

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Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates

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Abstract: This paper aims to explore the possible use of recycled concrete aggregates (RCAs) to produce concrete building blocks. Laboratory test and plant trial were carried out to manufacture concrete building blocks incorporating 75% RCAs. A series of tests were conducted to investigate the mechanical and durability properties of the recycled aggregate concrete (RAC) blocks. The compression and shear performances of masonry prisms built with RAC blocks and conventional mortars were experimentally studied too. Furthermore, the environmental impact of RAC blocks was studied using life-cycle assessment (LCA) method. Five different environmental impact categories (i.e., GWP, AP, EP, HTP, POCP) are calculated and comparatively analyzed. The effect of RCAs on the mechanical and durability properties, as well as the environmental impact of RAC blocks was investigated. The test results indicate that the incorporation of RCAs slightly declined the compressive strength and impaired the durability of the concrete blocks. Nevertheless, concrete building blocks incorporating 75% RCAs satisfied the strength, drying shrinkage and freeze-thaw resistance requirements for concrete building blocks specified by Chinese standard. The compressive and shear performances of masonry prisms constructed with RAC blocks are similar to those of conventional concrete masonry. RAC blocks have less environmental impact compared to normal concrete blocks. It is feasible to use RCAs to manufacture concrete building blocks along with environmental benefits. The use of RAC blocks plays a key role in ending the building life cycle and will improve the sustainable development of masonry structures.

Keywords: Recycled concrete aggregates (RACs), Concrete blocks, Mechanical properties, Durability, Life-cycle assessment (LCA).

1. Introduction

In recent years, the rapid developments of the building industry in China led to a huge quantity of construction and demolition (C & D) waste. On the other hand, a considerable number of nonrenewable natural resources (i.e., limestone and river sand) are depleted every year, resulting in a serious environmental problem. As of today, the rapid growth of the economy in China is at a cost of over-consumption in resources and severe destruction in the environment. In 2015, 3.9 billion tons of C & D wastes were generated in China, while approximately 5% of them were recycled. At the same time, 5 billion tons of natural aggregates were exploited (Fu, 2016). Over the last several decades, there are various solutions used for improving green footprint in concrete industry, such as the addition of Electric Arc Furnace (EAF) slags (Faleschini et al., 2015a, b), textiles (Awal and Mohammad Hosseini, 2016; Zhan and Poon, 2015) and fly ashes (Faleschini et al., 2015c; Alaka and Oyedele, 2016) as well as rubberized concretes (Hesami et al., 2016; Thomas and Chandra Gupta., 2016). In addition, recycling and reusing the waste concrete as recycled aggregates to produce RAC can conserve natural resources and reduce C & D wastes. Therefore, from the viewpoint of sustainable development of concrete, the successful application of RAC is of significant importance (Poon and Lam, 2008; Ling et al., 2013; Shan et al., 2017; Mallick and Radzicki, 2014).

Extensive programs have been carried out to study the physical, mechanical and durability properties of RAC in the last two decades (Dilbas, 2014; Zhang et al., 2017; Gao et al., 2012). In comparison with natural aggregates, recycled aggregates have lower strength and higher water absorption ability and are generally weaker, more porous. It is well known that the use of RCAs in RAC will jeopardize the mechanical and durability properties of RAC to a certain extent depending on the quality of the RCAs and the replacement percentage (Kwan et al., 2012; Kou et al., 2011; Gonzalez and Etxeberria, 2014). In addition, the structural performances of RAC elements and structures are a little inferior to those of structures made with conventional concrete. However, through reasonable design and proper mix procedure, RAC elements meet the requirement and can be used in practice as well as some successful applications of RAC in civil engineering have been obtained around the world over the last ten years (Nassar and Soroushian, 2012; Hanif et al., 2017; Mohammed et al., 2014).

Recently, the reliable use RACs to manufacture concrete bricks and blocks has attracted a lot of research interest (Matar and Dalat, 2012; Poon et al., 2006). When using recycled concrete aggregates to produce mechanized molded blocks and bricks, there are several advantages compared to the using RCAs in structural concrete. Firstly, mechanized molding machines are generally used to manufacture concrete blocks and bricks, thus the concrete mixtures are molded under a combined vibrating and compacting action. The workability, such as the slump of the concrete mixtures is not so important. Therefore, less amount water is used to produce the concrete mixes compared to RAC used for structural members. The lower water to cement (w/c) ratio will increase the strength of the concrete. Also, the less water content used in the concrete mixtures for the molded concrete blocks and bricks will significantly minimize the creep and shrinkage of the hardened concrete. Secondly, the molded blocks and bricks are compacted under a compression force and vibrating, resulting in a more compact structure and higher strength when compared with the RAC prepared with the conventional method (Poon et al., 2006).

Several studies have been conducted to investigate the mechanical and durability properties of blocks and bricks made with recycled aggregates. Poon et al. (2002) firstly implemented research to study the properties of the molded blocks and bricks prepared with recycled aggregates. The density, compressive and transverse strength of the RAC blocks was investigated. The test results indicated that 50% replacement of natural aggregates by recycled aggregates had little effect on the compressive strength of the blocks and bricks, but a higher percentage of replacement resulted in lower compressive strength for paving bricks and blocks (Poon et al., 2002). Poon and Chan (2006) conducted a research of using blended RCAs and crushed brick as aggregates to produce paving blocks. They concluded that the crushed clay brick declined the density, compressive and tensile strength of the paving blocks and increased the water absorption ability, which was due to the high water absorption of the crushed brick particles. Nevertheless, the paving blocks prepared with 50% and 25% crushed clay bricks met the compressive strength requirement for pedestrian areas and trafficked areas, respectively (Poon and Chan, 2006). The effects of aggregate-to-cement (A/C) ratios and types of aggregates on the performance of paving concrete blocks were experimentally studied by Poon and Lam (2008). they found that the compressive strength of the paving blocks declined with the A/C ratio increasing and was directly proportional to the crushing strength of the aggregates (Poon and Lam, 2008). Poon et al. (2009) studied the properties of concrete blocks manufactured with low grade recycled aggregates and concluded that the soil content in the recycled fine aggregate impaired the properties of the blocks. The mechanical strength of the blocks reduced with the increase of the low grade recycled fine aggregate content (Poon et al., 2009). Matar and Dalati (2012) investigated the effect of recycled aggregates on the compressive strength of the precast concrete hollow blocks and the rate of recycled aggregates content used in the blocks with suitable compressive strength was determined (Matar and Dalati, 2012). The mechanical behavior of masonry prisms manufactured with recycled aggregate mortars was investigated by Corinaldesi (2009). The bond strength, compressive and shear strength of masonry assemblages were measured and were related to the mechanical properties of mortars and brick. It was concluded that the mortar-brick bond strength and shear strength of the masonry manufactured with recycled-aggregate mortars seem to be superior to those of ordinary mortars (Corinaldesi, 2009). Lam et al. (2007) used recycled crushed glass as an aggregate to improve the performance of the pre-cast concrete paving blocks. Soutsos et al. (2011b) investigated the potential for using C&D waste as aggregate in the manufacture of a range of precast concrete products and concluded that there will be a significant cost savings where recycled demolition aggregate can be supplied to the block manufacturer at a price below that of newly quarried aggregates (Soutsos et al., 2011a).

These above studies have generally indicated that RCAs can be successfully used to replace natural aggregates to produce paving blocks and bricks and some successful applications of paving blocks made with RCAs in construction project have been reported (Poon, 2006). However, the majority of current studies were concerned with the physical, mechanical and durability performances of paving blocks and bricks made with RCAs. With regard to the using of RCAs to manufacture precast bricks and blocks for buildings, namely concrete building bricks and blocks, there has limited past research effort to the best knowledge of the authors. In addition, there has no past research effort to investigate the mechanical performances of masonry prisms constructed with RAC blocks and there is no reliable design method for RAC masonry structures.

With problems such as environmental pollution and consumption of energy, fired common clay bricks have been forbidden to use in China in last century. Concrete hollow blocks, which have several advantages over traditional masonry materials, such as high strength and labor productivity, light weight, convenience in construction, environmentally friendly, recently have been widely used in China to build multi-story residential buildings. This paper presents a recent study at Nanjing Tech University, which aims to investigate the possibility of using RCAs as the replacement of natural coarse aggregates in molded concrete building blocks. At first, the concrete hollow blocks incorporating 75% RCAs were prepared at the laboratory and the mechanical properties (compressive and transverse strength), durability (drying shrinkage and freeze-thaw resistance) of the RAC building blocks were studied carefully. In addition to laboratory trial, a plant trial was implemented at a local block manufacturing plant. RAC blocks were produced using the developed mix proportions by an industrial process and were then used to construct masonry prisms. A series of tests were carried out to study the mechanical performances of masonry prisms constructed with RAC blocks and conventional mortars. At last, the environmental impact of the precast RAC building blocks was investigated using LCA method. This investigation also aimed at providing more experimental data and reference for developing reasonable design regulation for RAC block masonry structures.

2. Experimental program

2.1 Materials

Ordinary Portland cement (OPC) with a 28d nominal compressive strength of 42.5 MPa was used as cementitious. The natural fine aggregate used was river sand, with an apparent density of 2615 kg/m^3, a water absorption in SDS (saturated dry surface) condition of 1.3% and a fineness modulus of 2.6. Crushed limestone with a maximum nominal size of 10 mm was used as natural coarse aggregates (NCAs). The RCAs used were obtained from 30 MPa waste concrete and were further crushed, cleaned, sieved and separated according to their dimension in the laboratory to produce RCAs with a nominal size of 4.75-10 mm. The gradation curves of fine and coarse aggregates are illustrated in Fig. 1, indicating that RCAs show a continuous granulometric curve and comply with Chinese standard JGJ 52-2006 (CABR, 2006). The physical and mechanical properties of NCAs and RCAs were experimentally studied and are shown in Table 1. RCAs have a lower density and higher water absorption compared to NCAs, which is mainly due to its greater porosity and adhered mortar. Furthermore, as shown in Table 1, RCAs have relatively favorable quality.

2.2 Concrete mixture proportions

Some performance requirements such as strength, drying shrinkage and freeze-thaw resistance are prescribed by Chinese standard-Normal Concrete Small Block (GB/T 8239-2014) for concrete building blocks, which are summarized in Table 2. The RAC blocks aim to meet the requirements and are expected to achieve compressive strength of not less than 10 MPa at the age of 28 days. Thus, the concrete mixtures are expected to achieve a 28-day compressive of not less than 25 MPa. A control mixture using only natural aggregates and a mixture of 75% NCAs (by weight) replaced by RCAs were prepared. Table 3 summaries the mix proportions for the concrete building blocks.

2.3 Production of precast RAC blocks

The proportioned materials were mixed in a drum mixer. Firstly, natural and recycled coarse aggregates, fine aggregates, and OPC were mixed for about 2 minutes. Then water was added to the mixtures and mixed for another 3 minutes to meet the requirements of molding. The procedure of mixing and adding water was iterated until the desired moisture content was obtained.

Concrete building blocks were fabricated in steel mould with a dimension of 390 mm ×190 mm × 190 mm (Fig. 2) using a dry-mixed method which simulated the actual industrial production process of concrete blocks (mixes were prepared with only sufficient water to produce a cohesive mix but with no slump/workability). After mixing the materials in a drum mixer, the mixed materials were laid into the mould and the steel mould was overfilled and a first compression force of 400 kN increased at a rate of 200 kN/min was applied for about 50 s to mechanically compact the materials in the mould. Excessive materials were then removed with a trowel in order to provide a good surface texture of the resulting blocks. After that, a second compaction force was applied at the same rate for approximately 60s. After casting, the fabricated concrete blocks, in the steel mould, were covered with a plastic sheet and were air cured at an ambient temperature of 20 ± 5°C and relative humidity of about 50% for 24 h. Subsequently, the blocks were moulded and were cured in air at room temperature and humidity until the day of testing.

In addition to laboratory trial, a plant trial was implemented at a local block manufacturing plant. The concrete blocks were produced using the developed mix proportions at commercial scale using truck batching. The mix proportion with 75% of the NCAs replaced by RCAs was used to produce the concrete blocks. The concrete hollow blocks were molded in an automatic mechanized block-making machine, cured in a steam bath at 60 ^{0}C for 12 h and further air cured at room temperature for 28 days. A total of 200 RAC blocks were manufactured at commercial scale using truck batching in this research. The formed building blocks (Fig. 2) were then used to manufacture masonry prisms.

2.4 Experimental procedures

The compressive strength of the blocks was evaluated in accordance with Chinese standard-Test Methods for the Concrete Block and Brick (GB/T 4111-2013). The compression tests were implemented after 28 days from the date of manufacturing. A compressive testing machine with a loading capacity of 2000 kN was used to measure the compressive strength of the blocks. The load was applied to the nominal area (i.e., 390 mm × 190 mm) of the concrete blocks and was increased with a constant speed of 5 kN/s. Prior to the compression tests, the concrete blocks were plastered with a thickness of 10 mm conventional mortar. The transverse strength of the blocks was measured in accordance with GB/T 4111-2013. Three steel rods with a diameter of 40mm were prepared to conduct three-point bending test with a supporting span of 140 mm.

The drying shrinkage of the concrete blocks was measured in accordance with GB/T 4111-2013. After 28 days of curing, the specimens were first immersed in water at room temperature for 4 days, and the initial length of the specimens was measured. After the initial reading, the specimens were then stored in the environmental chamber. The temperature and relative humidity inside the chamber were controlled at 20±5°C and not less than 80%, respectively. The length change of the specimen before and after drying was measured and the drying shrinkage was calculated. The process of drying and measuring continued until the final length measurement at 90 days was recorded.

The freezing and thawing resistance was evaluated following a procedure described by GB/T 4111-2013 for 15 cycles. Two groups, ten blocks were tested for 15 cycles. Before testing, all blocks were first immersed in water with a temperature of 15~25°C for 4 days. In a single cycle, the blocks were frozen in the air with a temperature less than -15°C and then were thawed in

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15~25°C water for 2 h. The changes in weight and compressive strength were calculated after 15 freeze-thaw cycles.

The compressive strength, shear strength and elastic modulus of RAC block masonry prisms were investigated in accordance with Chinese standard-Standards for Basic Mechanical Properties of Masonry (GB50129-2011T). The masonry prisms were constructed using RAC blocks constructed in the local plant and three different strength conventional mortars (i.e., 3.74 MPa, 5.48 MPa, 6.50 MPa) and divided into three groups (A, B, C). The compressive and shear strengths of the masonry prisms were determined by means of compression test and shear test, respectively. Fifteen 190 mm × 390 mm × 590 mm (Fig. 3a) prismatic specimens, among which nine were for compression test and six were for shear test, were constructed with three blocks and two 10 mm horizontal mortar joints for each kind of mortar. Tests were carried out at the age of 28 days and the load schematic diagram is shown in Fig. 3b, 3c. For compression test, the masonry prisms were capped with a thin layer of cement paste and were axially loaded using a compressive testing machine with a loading capacity of 2000 kN (Fig. 3b). The applied load and the vertical strain of the central part of the specimens were measured. For the shear test, the masonry prisms were shear loaded along the horizontal mortars of the specimen (Fig. 3c). In this way, the masonry prisms were shear loaded in the absence of vertical load stress. This generally results in a shear failure with the specimen splitting apart in a direction parallel to the load application. The load on the specimen was increased with a constant speed of 5 kN/s until failure of the specimen occurred. Elastic modulus was measured by means of strain gauges glued on the masonry prisms. In order to avoid the temperature effect on the measurements, a dummy gauge was placed on an unloaded specimen.

3. Environmental impact assessment of RAC blocks

Over the last fifteen years, high volumes of concrete were annually used in China, resulting in significant environmental pollution. Therefore, from the viewpoint of sustainable development, the environmental impact assessment of concrete production is of great importance. The LCA method studies the environmental impact and resources used throughout a product's life-cycle from raw material acquisition through production, use, maintenance, recycling, and disposal as well as reveals areas with improvement potential (Finnveden, 2009; Rehl and Müller, 2015; Mah et al., 2017). In this paper and for the manufacturing process of RAC blocks, a comparative analysis on the environmental impact of RAC blocks is conducted using LCA method. Several previous researches have investigated the environmental issues of the production of the RAC and its product and compare that with conventional concrete (López Gayarre et al., 2016; Corinaldesi, 2009).

The LCA based on ISO 14040 series consists of four stages: (1) Goal and Scope Definition; (2) Inventory Analysis; (3) Impact Assessment; (4) Interpretation (ISO standards 14040 and 14044, 2006). In the goal and scope definition, the product system, the system boundary and the functional unit are specified. The functional unit is the basis for comparison throughout the study (ISO standards 14040 and 14044, 2006). The system boundary includes the extraction of raw materials, major material production and preparation processes, transportation of materials and production of the product. The life-cycle inventory (LCI) collects the emissions data (i.e., CO_2、NO_x、CH_4、SO_2、CO、NMVOC、N_2O、NH_3 and PM_{10}) relevant to the production of concrete blocks. In the life-cycle impact assessment (LCIA) stage, the potential human and ecological impact are estimated. Classification and characterization of the impact categories are involved in this stage. The life-cycle interpretation is of great importance to "identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively" (ISO standards 14040 and 14044, 2006).

This paper employed LCA approach to assessing the cradle-to-gate environmental impact of the RAC blocks. The main goal for this paper is to determine the environmental impact generated in the whole set of stages defined in the manufacturing of the blocks. The functional unit used in this study is the volume of concrete (i.e., 1 m^3) which would be used to manufacture the concrete blocks. The system boundary includes raw materials extraction (e.g., limestone, sandstone, aggregate, sand), materials production, transportation of materials, blocks production, and ends at the gate of block manufacturing plant with the final product being concrete blocks ready to be used at the construction site. Five different environmental impact categories, including the global warming potential (GWP), the human toxicity potential (HTP), the eutrophication potential (EP), the acidification potential (AP) and the formation of oxidant air or photo-chemical fog in the atmosphere potential (POCP), are calculated based on the Dutch LCA handbook (Guinée et al., 2002). The RCAs used in this study is taken from a demolished building in Nanjing. After crushing, the waste concrete was transported to a local block plant and processed into aggregate finished products used to manufacture blocks. The recycled aggregate is transported by trucks, and the distance of transportation is 20 km. The natural aggregates are extracted from a quarry located in Jiangxi Province and transported by rail to Nanjing. The distance of transportation is estimated to be about 1000 km as calculated from Google Maps. The sand and cement used were purchased from local producers located 50 km away from the block plant, respectively. Table 4 summarizes the entire LCI inventory for concrete block production. The sources for the data showed in Table 4 for life cycle inventory include opened literatures, interviews with local operators and manufacturers, monitoring analysis and field investigation as well as database developed by China Centre of National Material Life Cycle Assessment (CNMLCA, 2010) in Beijing University of Technology and Chinese Life Cycle Database (CLCD, 2012) developed by Integrated Knowledge for our Environment (IKE) in Sichuan University.

4. Results and Discussions

4.1 Mechanical and durability properties of concrete blocks

The test results, including compressive, transverse strength of the blocks, which is the average value of five specimens each time are summarized in Table 5. In terms of both failure pattern and ultimate strength, the RAC block and normal block performed similarly. The compressive strength of RAC blocks is 4.9% less than that of the normal blocks, which might be attributed to the adhered mortar and more porous structure of the RCAs. The compressive strength of the RAC blocks manufactured in the local plant is also shown in Table 5, which is 6.7% less than that of the normal blocks prepared in the laboratory trials using the same mix proportion, indicating that the field trial mixes prepared similar strength to the laboratory mixes.

The drying shrinkage results, which were measured at 35 and 90 days are also shown in Table 5. Each presented value is the average of three measurements. The drying shrinkage of the RAC blocks is 7.7% higher than that of normal blocks, which might be attributed to the higher porosity additional mortar attached to the RCAs. In additon, The shrinkage of the RAC blocks measured in this test (i.e., 0.042%) is consistent with the results obtained by Poon et al. (2002) (i.e., <

0.06%). The freeze-thaw resistance in terms of the percent change in weight and compressive strength for all specimens is presented in Table 5. Chinese standard GB/T 8239-2014 requires a maximum weight loss (5%) and strength reduction (20%) for concrete building blocks. Although the mass and strength loss of the RAC blocks are slightly higher than those of normal blocks, the reduction of weight and strength of RAC blocks was 0.82% and 11.8%, respectively, indicating that RAC blocks satisfy the freeze-thaw resistance requirement prescribed by GB/T 8239-2014.

According to the test results, although the replacement of the natural aggregates by recycled aggregates resulted in lower strength values and inferior durability, the concrete blocks containing 75% recycled aggregates still satisfy the performance requirements specified by Chinese standard GB/T 8239-2014 for compressive and transverse strength, drying shrinkage and freeze-thaw resistance for concrete building blocks (Table 2). Therefore, it can be concluded that it is feasible to produce concrete building blocks containing RCAs by an industrial process.

4.2 Compressive strength of masonry prisms

It is well known that the mechanical behaviors, including shear and compressive strength, of masonry prisms, depend much more on the units and mortars than on the intrinsic mechanical properties of the blocks and mortars. Thus, theoretically, the RCAs used to manufacture concrete blocks will not significantly affect the mechanical behavior of the masonry prisms. The crack patterns of the masonry prisms subjected to axial load are shown in Fig. 4. In terms of both first-cracking and failure mode, the masonry assemblages prepared with RAC blocks performed similarly when compared to conventional concrete masonry prisms. Table 6 presents the test results, including compressive strength and elastic modulus of each specimen. As can be seen from Table 6, the compressive strength of the masonry increased with the increase of the mortar strength. By comparing the values of the compressive strength of the RAC blocks masonry to the conventional concrete block, it can be found that the compressive strength of the RAC masonry prisms is similar to that of the conventional concrete block masonry, which is mainly due to the reason that the compressive strength of the masonry is dependent on the strengths of unit and mortars.

According to Chinese standard GB50003-2011, the compressive strength of the masonry can be calculated using the following equation:

$$f_m = k_1 f_1^{\alpha}(1 + 0.07 f_2)k_2 \quad (1)$$

Where f_1, f_2 is the average compressive strength of the units and mortars, respectively; α is the factor considering the height of the unit and a value of 0.9 is adopted, k_1 is the factor considering the unit type and a value of 0.46 is adapted for conventional masonry, k_2 is an adjust coefficient considering the compressive strength of the mortars and a value of 1.0 is adopted.

Nonlinear regression analysis using test results was carried out and k_1 was considered as the main parameter and a value of 0.49 was obtained by the least square method, which is slightly higher than the value proposed by GB 50003-2011. Therefore, from the viewpoint of conservation, the compressive strength of the masonry built with RAC blocks can be calculated using equation proposed by GB 50003-2011. Table 6 shows the compressive strength predictions for the masonry according to GB 50003-2011 and the comparisons with test results. It is clear that there is a close agreement between the predictions and test results. The average value and standard deviation of the ratios between test results and predictions are 1.06 and 0.13, respectively.

The strain-stress diagrams of the masonry prisms are shown in Fig.5. The strains are the average of the displacement values measured on both sides of the prisms, meaning that each value represents the average of two readings. It can be seen that the strain-stress diagrams of the masonry prisms built with RAC blocks are similar to those of conventional concrete masonry prisms. It is widely accepted that the non-linear performance of the masonry prisms is mostly governed by the mortars. Therefore, RAC blocks will not significantly affect the behavior of the masonry prisms under compression. In addition, the stress-strain diagrams are clear non-linear shape, indicating significant inelastic deformation, which is mainly due to the damage in the prisms, caused by cracking of the mortars and blocks (Sayed-Ahmed and Shrive, 1996).

The model to represent the stress-strain relationship of masonry proposed by Zhang (Zhang and Tang, 2002) is given by:

$$\varepsilon = -\frac{1}{\xi}\ln(1-\frac{\sigma}{f_m}) \tag{2}$$

Where σ, ε is the axial compression stress and strain of the walls, respectively; ξ is a factor considering the compressive strength of masonry. For conventional clay brick masonry, $\xi = 460\sqrt{f_m}$.

The equation proposed by Yang (Yang, 2008) is shown as follows:

$$\frac{\sigma}{f_m} = \frac{\varepsilon/\varepsilon_0}{a + b(\varepsilon/\varepsilon_0)} \qquad (\varepsilon \le \varepsilon_0) \tag{3}$$

Where coefficients a and b are constants and need to be determined experimentally; ε_0 is the maximum axial compression strain of the walls.

Based on the statistical analysis of test results, above two models were used to fit the stress-strain curves of the RAC masonry. The regression expression obtained by the least square method for ξ is $\xi = 404.5\sqrt{f_m}$ and the value of a and b is 0.26 and 1.07, respectively. The comparisons of proposed models predict curves with the measured curves are illustrated in Fig. 6. There is a good agreement which can be found between the models and the measured curves as shown in Fig. 6.

The elastic modulus of the masonry prisms is also summarized in Table 7. As shown in Table 7, the elastic modulus of the masonry prisms increases with the mortar strength increasing, which is due to the reason that the deformation of the masonry is mainly dependent on the mortars. In addition, the masonry prisms constructed with RAC blocks showed similar elastic modulus with respect to the conventional concrete masonry prisms. Generally, the elastic modulus of the masonry as a composite system includes the effect of the mortar and unit. Thus, the less stiff blocks made with RCAs will not significantly affect the deformation behavior of the masonry prisms.

The Eurocode 6 (DIN EN-1996-1-1) and Chinese standard GB 50003-2011 both indicate that the secant elasticity modulus of the masonry can be calculated as follows:

$$E = \alpha f \tag{4}$$

Where f is the compressive strength of the masonry, α is an empirical factor and independent of the unit geometry and mortar type and related to the strength of the mortars.

Equation (4) gives only an approximate estimate of the elastic modulus of the masonry. The elastic modulus predictions of the masonry prisms built with RAC blocks according to GB50003-2011 and the comparisons with test results are illustrated in Table 7, showing the predictions are slightly less than the test results. Thus, the elastic modulus of the masonry prisms built with RAC blocks can be calculated according to GB50003-2011.

4.3 Shear strength of masonry prisms

The failure pattern of the masonry prisms manufactured with RAC blocks under shear was produced by the separation along the interface between horizontal mortars and blocks, which is similar to that of the conventional concrete block prisms. The ultimate load and shear strength of the masonry prisms are shown in Table 8. As can be seen from Table 8, the shear strength of the masonry increased with the increase of the strength of the mortars. Furthermore, the shear strength of the RAC masonry prisms is slightly less than that of the conventional concrete masonry. The reason probably lies in the higher porous structure and higher water absorption of the RAC blocks. It is well known that the shear strength of the masonry is mainly dependent on the strength of the mortar. The RAC blocks will lead to a higher loss of water for the mortars, resulting in a lower strength of the mortars and shear strength of the masonry.

According to Chinese standard GB50003-2011, the shear strength $f_{v,m}$ of the masonry can be calculated as follows:

$$f_{v,m} = k_5\sqrt{f_2} \tag{5}$$

Where f_2 is the average compressive strength of the mortars, k_5 is a regression factor related to the type of the unit and a value of 0.069 was proposed by GB50003-2011 for conventional concrete block masonry.

The regression value obtained for k_1 at least square method using test results is 0.06. Therefore, the shear strength of the masonry built with RAC blocks can be calculated in the following form:

$$f_{v,m} = 0.06\sqrt{f_2} \tag{6}$$

The shear strength predictions using equation and the comparison with test results are shown in Table 8. It is clear that there is a close agreement between the predictions and test results. The ultimate shear strength predicted from Eq. (6) is slightly less than the test results. The average value and standard deviation of the ratios between test results and predictions are 0.99 and 0.12, respectively.

4.4 Environmental impact assessment

The calculated environmental impact categories associated with the production of 1 m^3 and RAC blocks and normal concrete blocks are illustrated in Table 9, which involve containment emissions from all raw materials extraction, materials production, the production of blocks in the plant, and transportation processes taking place within the system boundary. As shown in Table 9, when compared to RAC blocks, normal blocks result in slightly higher GWP, AP, EP, HTP, POCP, which is mainly attributed to the much longer transportation distance and different transportation mode of NCAs. The GWP from the transportation of RACs is 60% less than that of NACs due to the number of materials conveyed and transportation distance and mode, as shown in Table 9.

The calculated total GWP for concrete block production (kg of CO_2-eq/m^3 of concrete) and the contribution to the GWP of the major concrete ingredients used are further studied in detail through Fig 7-9. With a total of about 324 kg of CO_2-eq, the total GWP for conventional concrete blocks is 5.53% larger than that of the RAC blocks. In addition, the cement production is the highest source of emissions, which is about 87.7% of the total GWP. As can be seen from Fig.8, the transportation of all materials to the block plant is the second highest source of emissions, which is about 10.3% of the total GWP. This is consistent with the results obtained by Celik et al. (2015).

When we further study the sources of the major GHG emission from other ingredients, their mass contribution remains almost constant for RAC blocks and normal concrete blocks, about 1.79 kg for the fine aggregates (0.55%), 2.13 kg for the block production (0.65%), as shown in Fig. 8. The coarse aggregates are the only exception. The GHG emission from the production of RCAs is 56.0% higher than that of the NCAs, as shown in Fig. 8, which is in accordance with the result presented by López Gayarre et al. (2016). This is mainly attributed to the electric power consumption during the crushing of recycled aggregate.

For a better comprehension, the global values of other four impact categories taken from Table 9 and the relative comparison between the RAC blocks and normal concrete blocks have been arranged and plotted in Fig. 9, which includes the human toxicity, the eutrophication, the acidifying and the formation of POCP. Similar to GWP, AP appears to increase with an increase in NCAs use, mostly because of fuel combustion during transportation. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). As also can be seen from Fig. 9, the use of coarse aggregates coming from waste concrete has a 33.61 to 65.14 percent decrease over normal concrete blocks in the other three environmental impact types. Furthermore, a subsequent landscape impact and exploitation of nonrenewable natural resources is being reduced using the recycled aggregates, as the natural aggregates extraction would be declined. Therefore, it might be concluded that the use of recycled aggregates to make RAC blocks does have significant beneficial impact on the environment.

5. Conclusions

This research aims to develop a technique for manufacturing concrete building blocks incorporating RCAs. Laboratory test and plant trial were carried out to manufacture the concrete blocks incorporating 75% RCAs. A series of tests were carried out to investigate the mechanical and durability properties of the RAC blocks as well as the mechanical performances of the masonry prisms constructed with RAC blocks. The environmental impact of the RAC blocks was studied using LCA method. The test results and discussions allow the following conclusions to be drawn:

(1) The RCAs slightly impaired the mechanical and durability properties of the concrete blocks. Nevertheless, the concrete building blocks made with 75% RCAs exhibit favorable mechanical and durability performances and satisfy the performance requirements specified by Chinese standard for concrete building blocks.

(2) The strength of the RAC blocks manufactured in the local plant is similar to that of the laboratory trials, indicating that it is viable to produce RAC blocks used in multi-story buildings by an industrial process.

(3) The compressive behavior, including compressive strength, elastic modulus and stress-strain relationship, and shear performance of masonry prisms constructed with RAC blocks and conventional mortars are similar to those of normal concrete masonry assemblages.

(4) The environmental impacts from the production of RAC blocks are less than that of normal concrete blocks, which is mainly attributed to the much longer transportation distance of the NCAs.

It is feasible to replace NCAs with RCAs to produce concrete blocks along with environmental benefits. Further research is needed to study the structural behavior, including the compressive and seismic performance of RAC blocks masonry walls. It is hoped that the successful application of RAC building blocks may further promote the sustainable development of masonry structures.

Acknowledgments

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notation list

RCAs recycled concrete aggregates

NCAs natural coarse aggregates

RAC recycled aggregate concrete

LCA life-cycle assessment

LCI life-cycle inventory

LCIA life-cycle impact assessment

GWP the global warming potential

HTP the human toxicity potential

EP the eutrophication potential

AP the acidification potential

POCP the formation of oxidant air or photo-chemical fog in the atmosphere potential

GHG greenhouse gas

C & D construction and demolition

EAF Electric Arc Furnace

w/c water to cement

A/C aggregate-to-cement

OPC Ordinary Portland cement

SDS saturated dry surface

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List of symbols

f_1, f_2 : The average compressive strength of the units and mortars (MPa, MPa)

k_1, k_2 : The factor considering the unit type and The adjust coefficient considering the compressive strength of the mortars (−)

α : The factor considering the height of the unit (−)

f_m : The average compressive strengths of masonry prisms (MPa)

ξ : The factor considering the compressive strength of masonry (−)

σ : The axial compression stress of the walls (MPa)

f : The compressive strength of the masonry (MPa)

α : An empirical factor related to the strength of the mortars

E : The secant elasticity modulus of the masonry (MPa)

$f_{v,m}$: The shear strength of the masonry (MPa)

f_2 : The average compressive strength of the mortars (MPa)

k_5 : The regression factor related to the type of the unit (−)

ε : The axial compression strain of the walls ($\mu\varepsilon$)

ε_0 : The maximum axial compression strain of the walls ($\mu\varepsilon$)

a, b : Regression factor (−)

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List of figures

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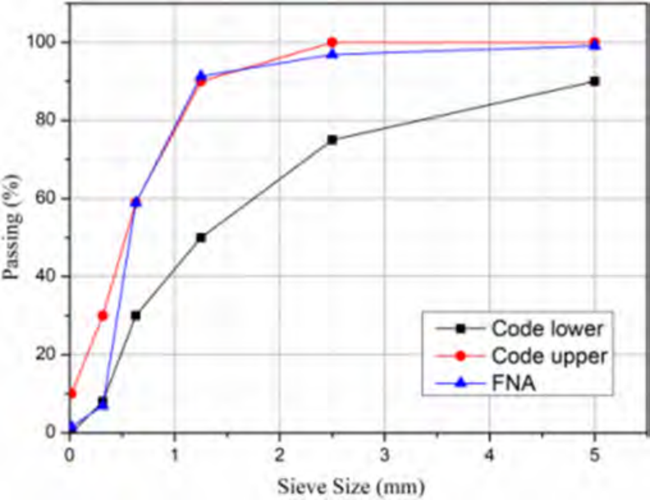
Highlights:

- The mechanical and durability properties of RAC blocks are experimentally studied.
- Concrete blocks incorporating 75% RCAs exhibit favorable performances.
- RAC masonry have similar mechanical behavior compared to normal concrete masonry.
- RAC blocks have less environmental impact than normal concrete blocks.
- It is viable to use RCAs to produce concrete building blocks by an industrial process.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Sieve Size (mm)
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Code upper
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40
60
80
100
0
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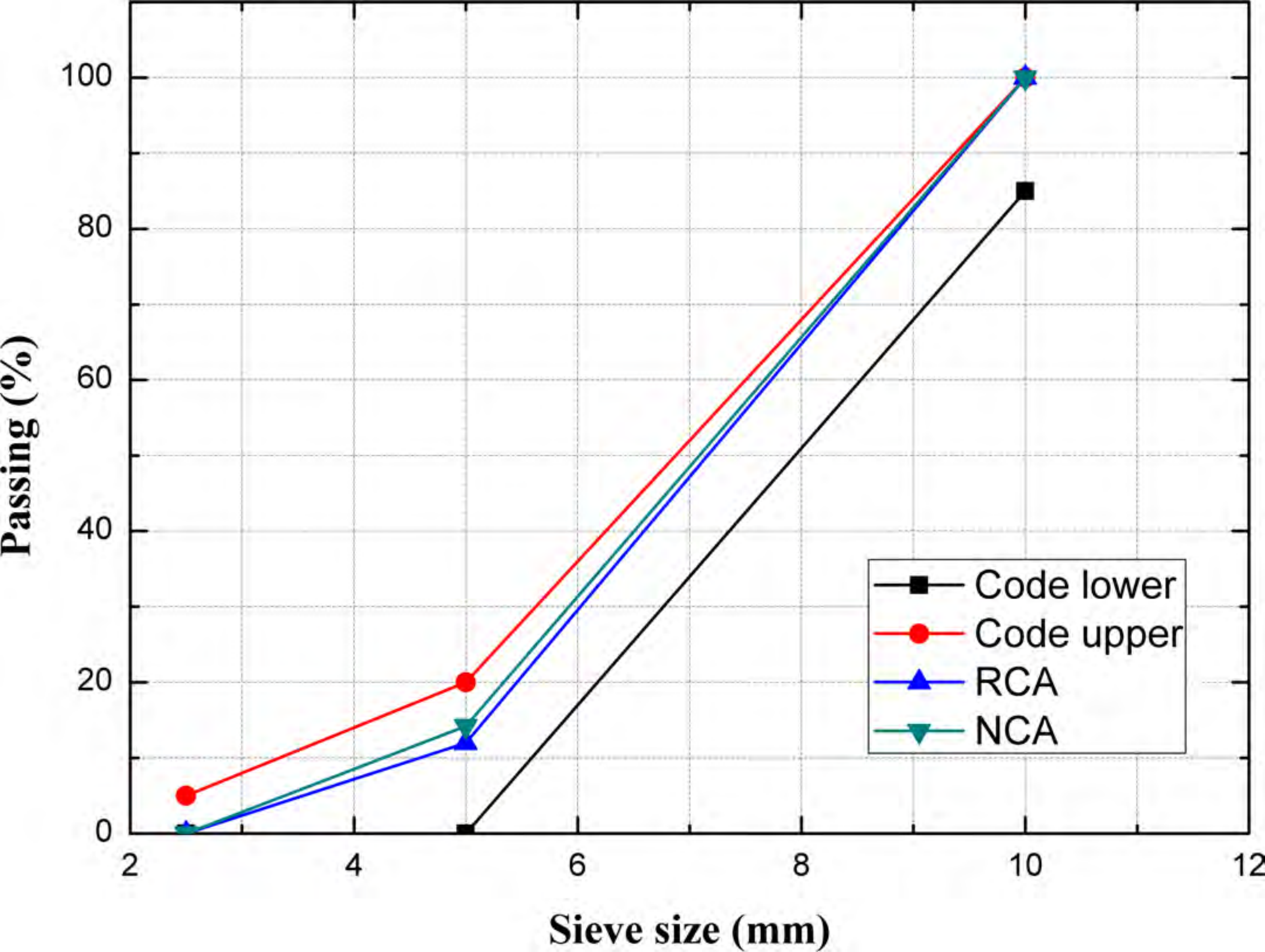
2
3
4
5



Passing (%)
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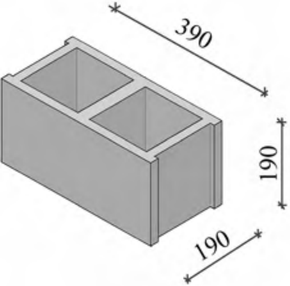
20
40
60
80
100
2
4
6
8
10
12
Sieve size (mm)
Code lower
Code upper
RCA
NCA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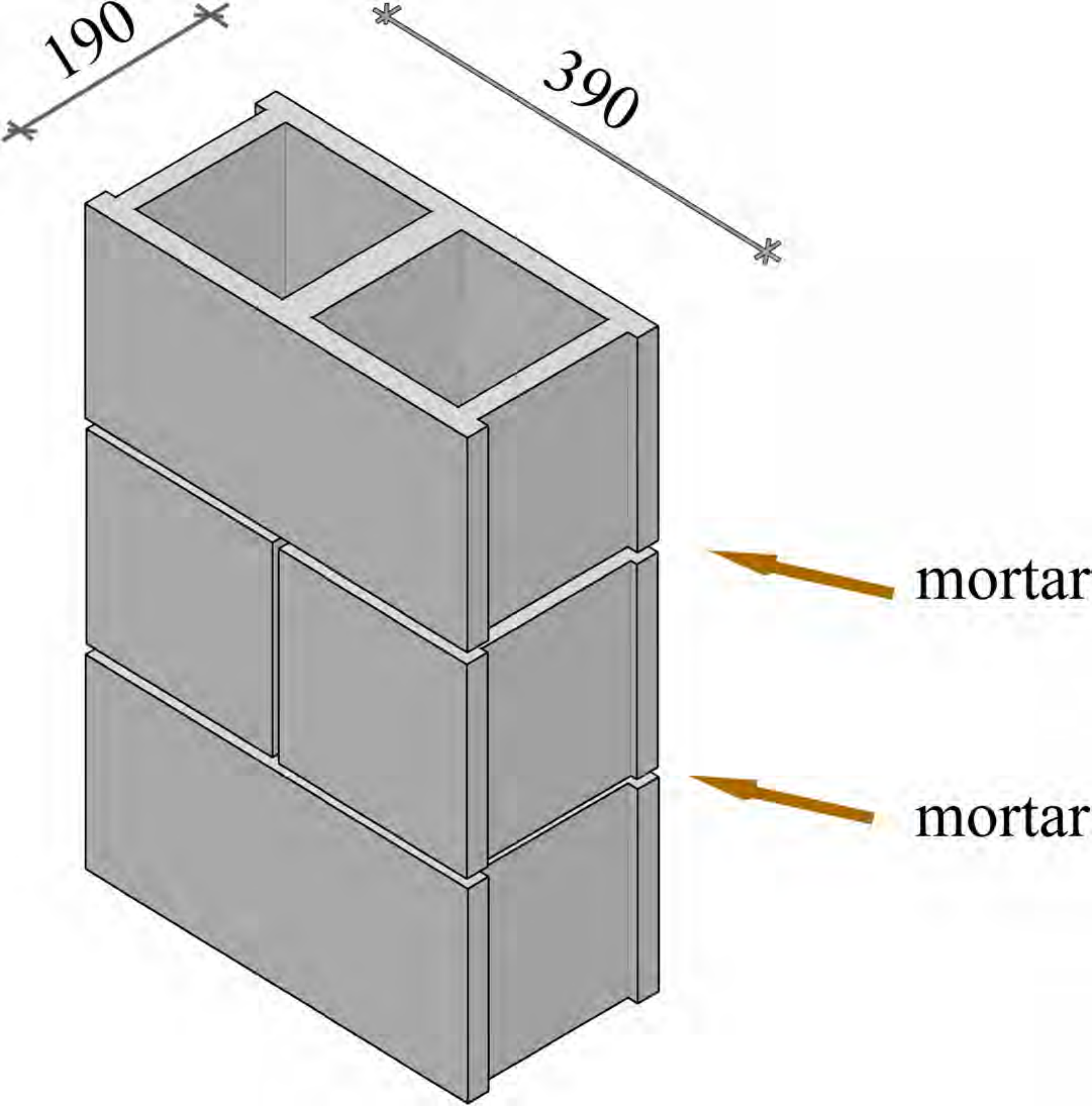
190
190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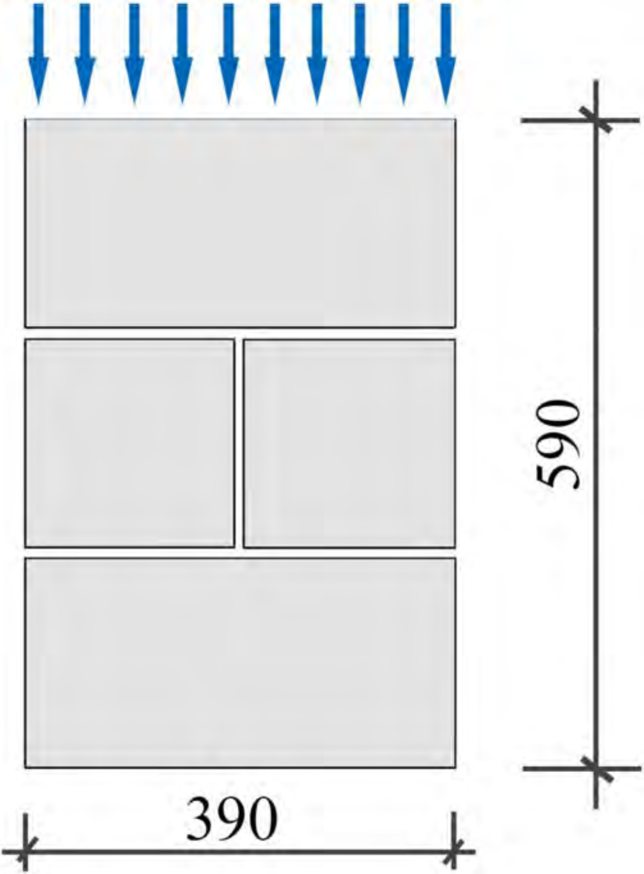
mortar
mortar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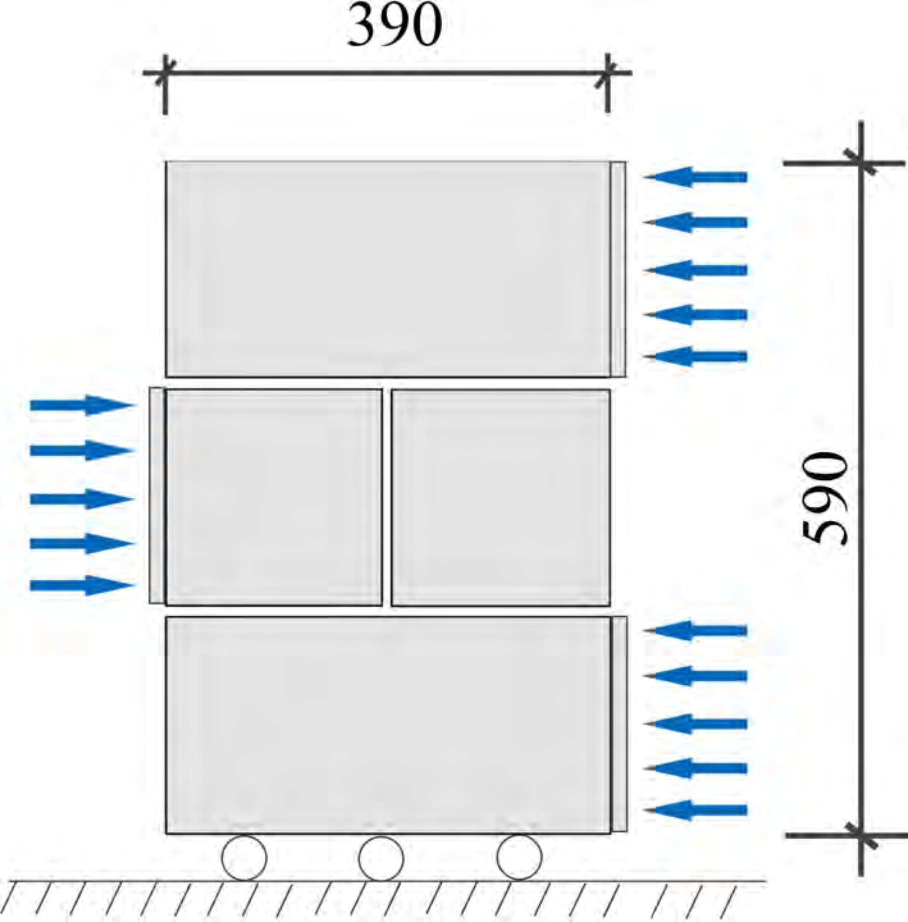

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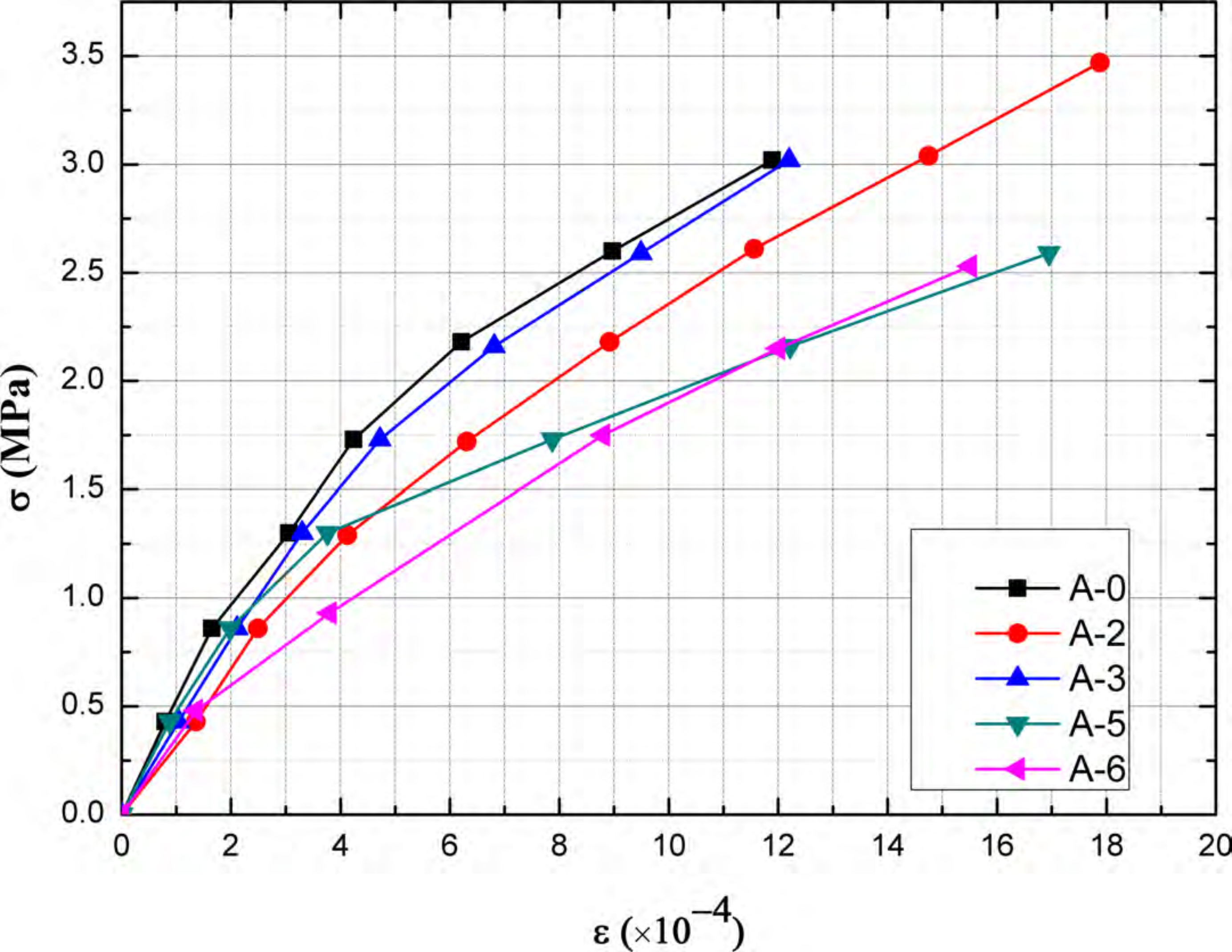
σ (MPa)
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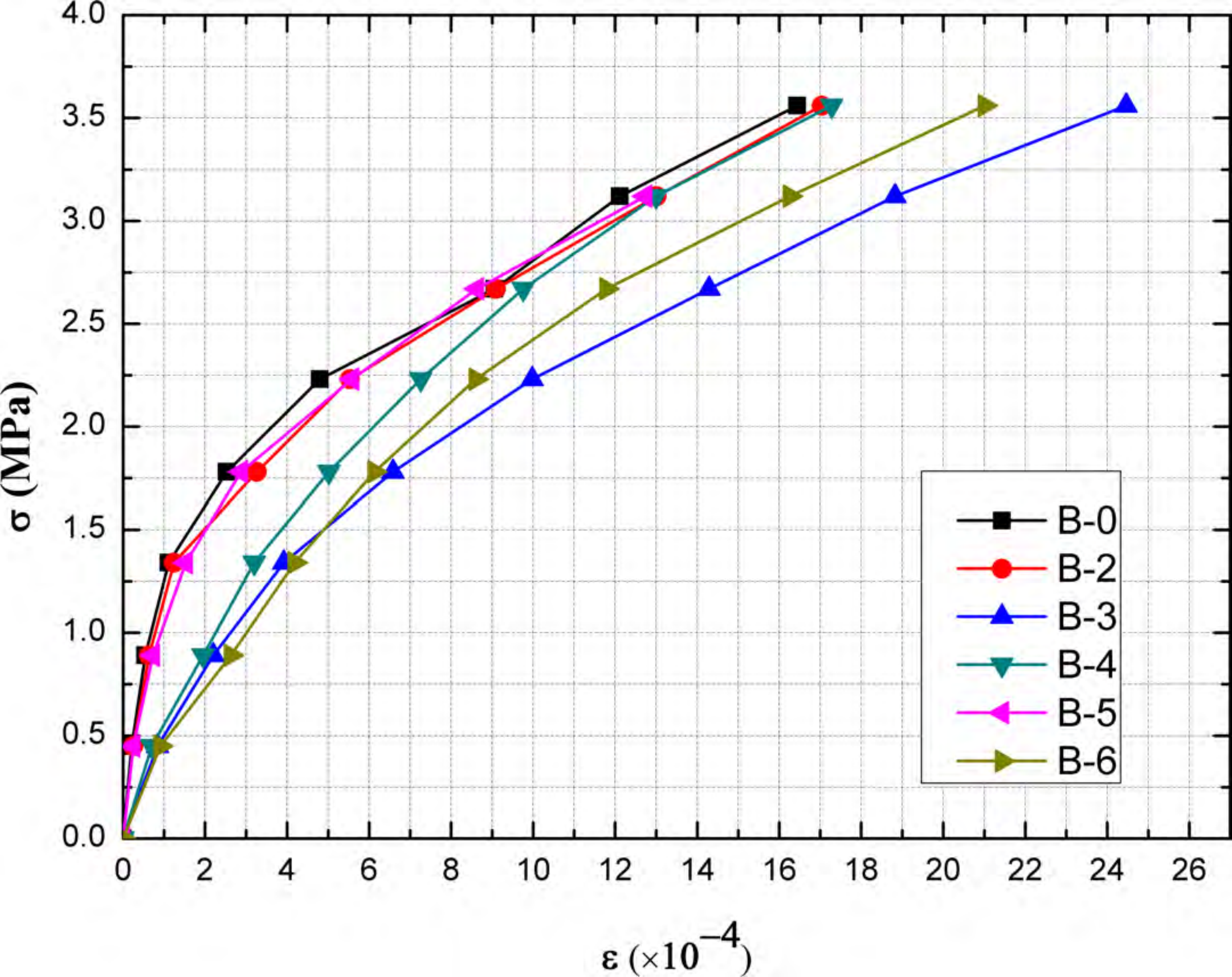
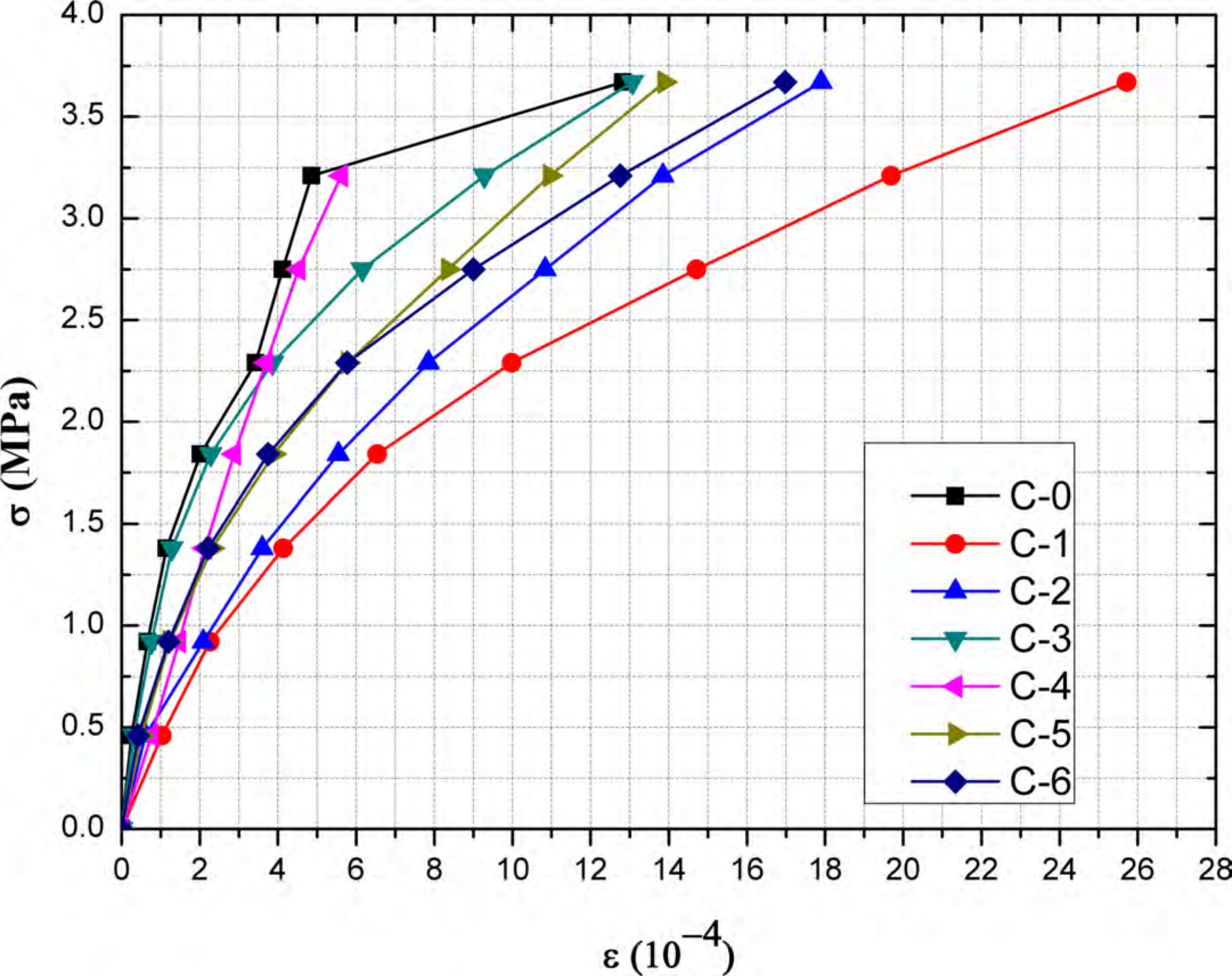
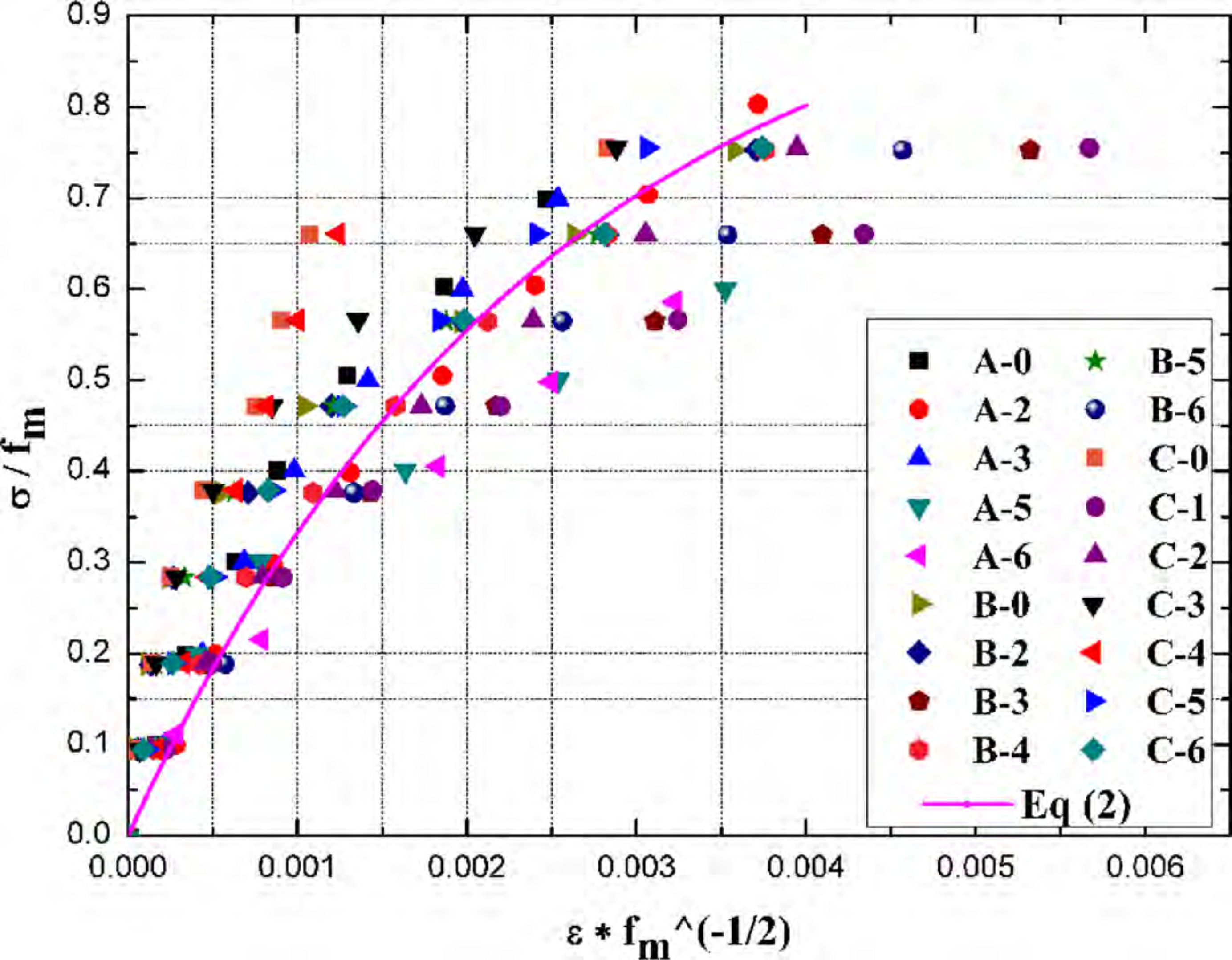
1.0
1.5
2.0
2.5
3.0
3.5
0
2
4
6
8
10
12
14
16
18
20
ε (×10−4)
A-0
A-2
A-3
A-5
A-6



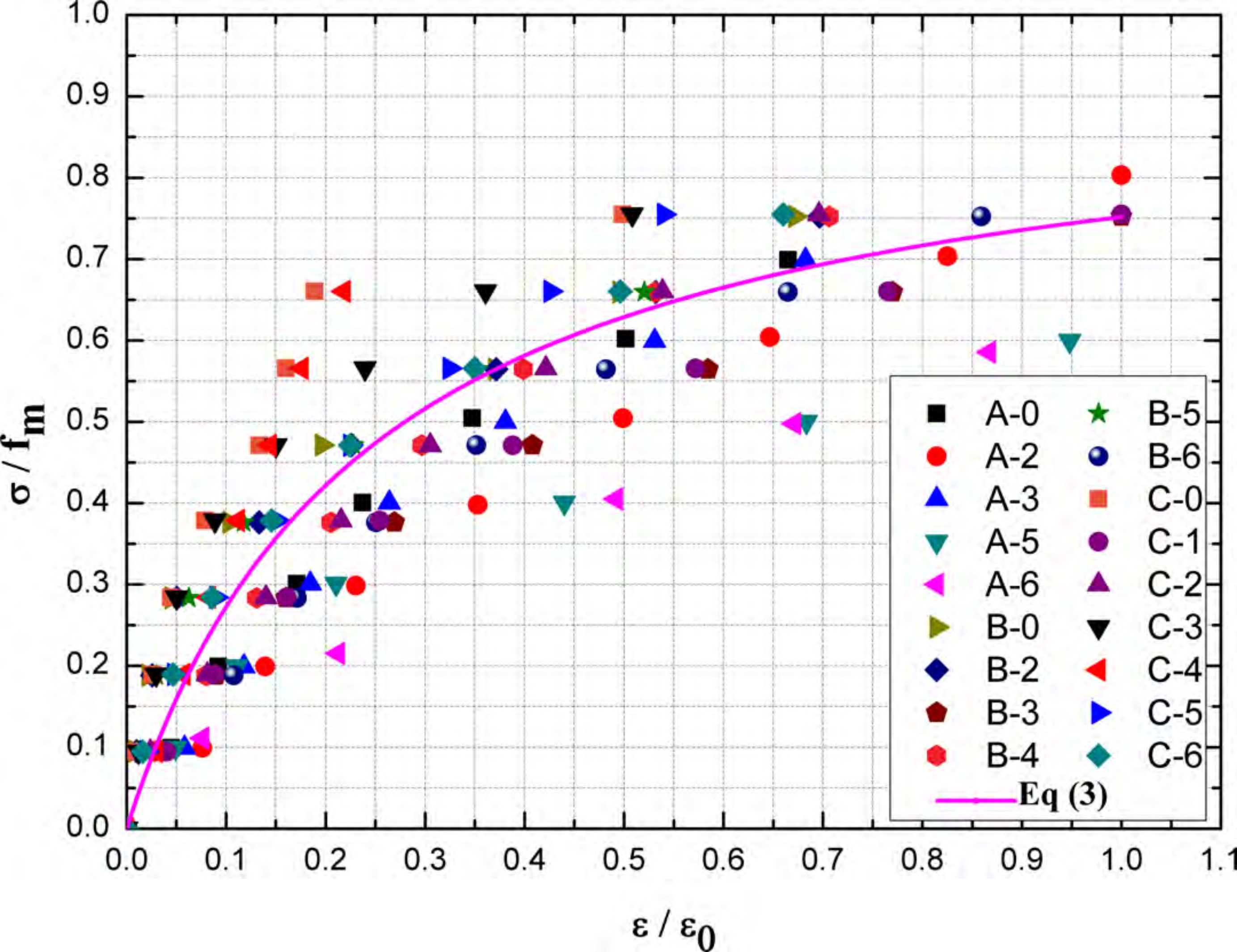
σ (MPa)
ε (×10−4)
B-0
B-2
B-3
B-4
B-5
B-6



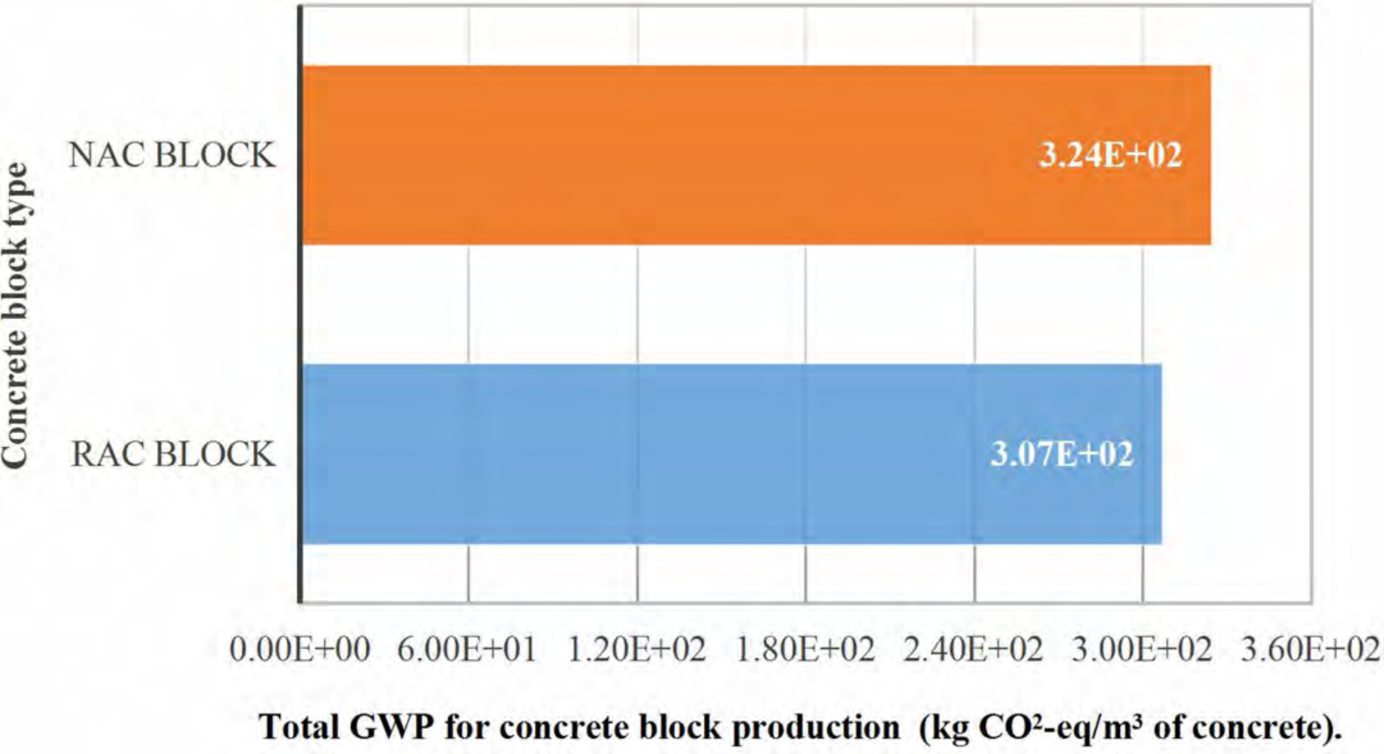
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
σ (MPa)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
ε (10^{-4})
C-0
C-1
C-2
C-3
C-4
C-5
C-6



σ / f_m
ε * f_m^(-1/2)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.000
0.001
0.002
0.003
0.004
0.005
0.006
A-0
A-2
A-3
A-5
A-6
B-0
B-2
B-3
B-4
B-5
B-6
C-0
C-1
C-2
C-3
C-4
C-5
C-6
Eq (2)



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
σ / f_m
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
ε / ε_0
A-0
A-2
A-3
A-5
A-6
B-0
B-2
B-3
B-4
B-5
B-6
C-0
C-1
C-2
C-3
C-4
C-5
C-6
Eq (3)


Concrete block type
NAC BLOCK
RAC BLOCK
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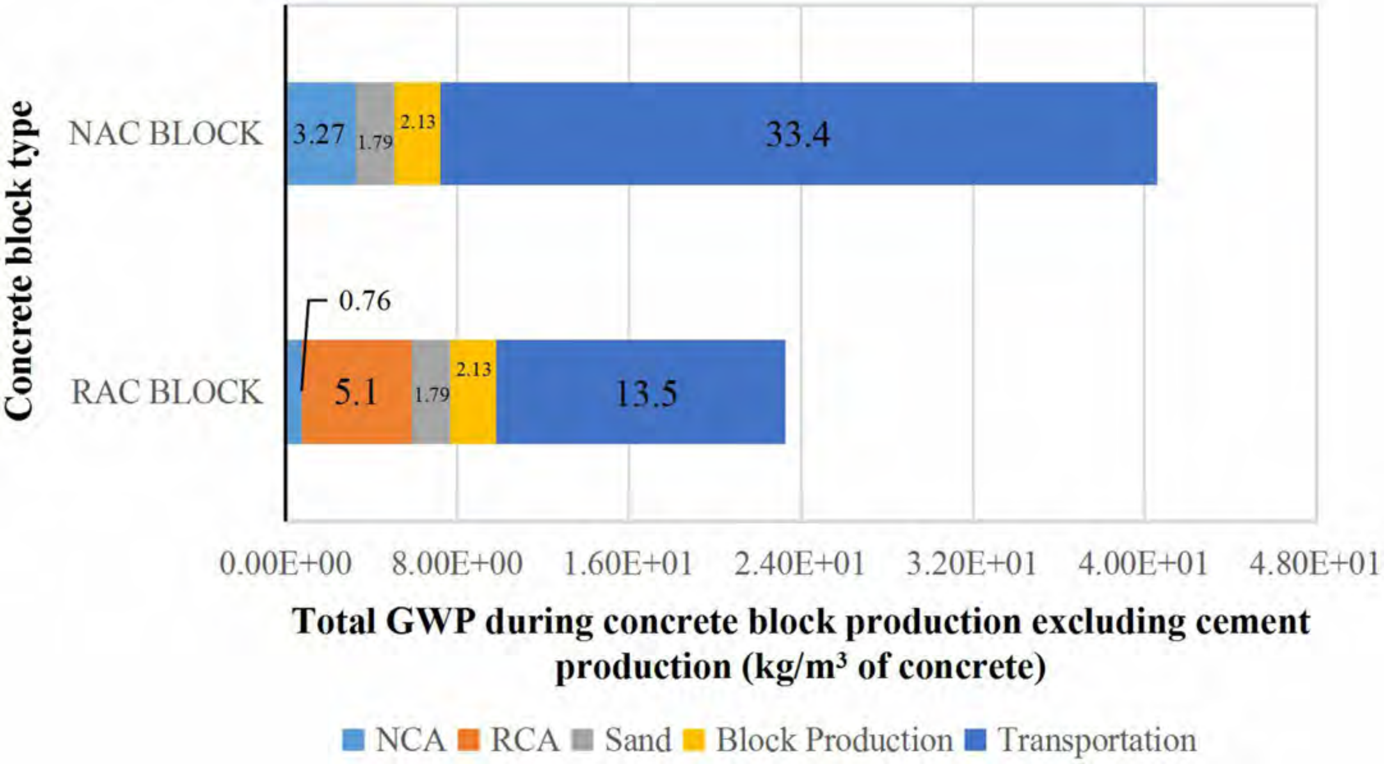
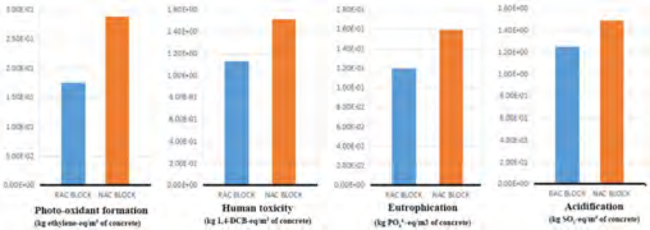
3.07E+02
0.00E+00
6.00E+01
1.20E+02
1.80E+02
2.40E+02
3.00E+02
3.60E+02
Total GWP for concrete block production (kg CO²-eq/m³ of concrete).


Concrete block type
NAC BLOCK
RAC BLOCK
3.27
1.79
2.13
33.4
0.76
5.1
1.79
2.13
13.5
0.00E+00
8.00E+00
1.60E+01
2.40E+01
3.20E+01
4.00E+01
4.80E+01
Total GWP during concrete block production excluding cement production (kg/m³ of concrete)
NCA
RCA
Sand
Block Production
Transportation



RAC BLOCK
NAC BLOCK
Photo-oxidant formation
(kg ethylene-eq/m³ of concrete)
Human toxicity
(kg 1,4-DCB-eq/m³ of concrete)
Eutrophication
(kg PO4³⁻-eq/m3 of concrete)
Acidification
(kg SO2-eq/m³ of concrete)

Table 1. Properties of RCAs and NCAs

Properties	RCA	NCA
Dry specific density (kg/m^3)	2627	2725
Surface dry specific density (kg/m^3)	2748	2843
Dry bulk density (kg/m^3)	1405	1522
Water absorption (%)	3.8	0.5
Nominal size (mm)	4.75-10	

Table 2. Performance requirements for concrete building blocks prescribed by GB/T 8239-2014

Requirements	GB/T 8239-2014
Compressive strength (MPa)	≥7.5
Drying shrinkage (%)	≤0.045
freeze-thaw resistance	≥D15

Table 3. Concrete mixtures composition

Mixture notation	Mixing water (kg/m^3)	Cement (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	River sand (kg/m^3)	Additional water (kg/m^3)
Control	155	316.17	2041.13	0	738.40	0
RB-75	155	316.17	1154.93	886.20	738.40	20

Table 4. Life cycle inventory for concrete block production

Category	Cement (kg/kg)	NCA (kg/kg)	RCA (kg/kg)	Sand (kg/kg)	Transportation (kg/t·		Block Production (kg/kg)
					Truck_18t	Rail	
CO_2	8.85E-01	2.79E-03	5.71E-03	2.34E-03	1.03E-01	2.42E-02	8.53E-04
NO_x	1.79E-03	2.00E-05	2.40E-05	1.52E-05	1.94E-03	3.89E-04	2.33E-05
CH_4	5.80E-04	1.47E-06	1.00E-06	3.72E-06	3.64E-04	2.35E-05	7.85E-07
SO_2	1.05E-03	3.00E-06	5.00E-06	9.49E-06	9.18E-05	3.31E-05	1.04E-04
CO	2.14E-03	5.00E-06	1.00E-06	4.19E-06	7.74E-04	1.28E-04	2.45E-06
NMVOC	3.07E-04	2.00E-06	3.00E-06	2.13E-07	4.69E-04	2.39E-04	2.92E-06
N_2O	2.22E-06	2.08E-08	8.45E-08	3.81E-08	5.07E-06	6.36E-08	6.08E-08
NH_3	3.91E-05	1.02E-08	1.00E-08	7.24E-09	1.43E-07	2.28E-08	4.50E-09
PM_{10}	4.22E-06	3.50E-07	1.70E-07	1.20E-07	4.99E-05	2.10E-05	3.70E-07

Table 5. Mechanical and durability properties of concrete blocks

Mixture notation		Compressive strength (MPa)	Transverse strength (MPa)	Drying shrinkage (%)		Freeze-thaw resistance (%)	
				35 d	90 d	mass loss ratio	strength loss ratio
Normal blocks		9.86	1.59	0.036	0.039	0.79	11.5
RAC block	Laboratory	9.38	1.55	0.038	0.042	0.82	11.8
	Plant trial	8.76	1.43	-	-	-	-

Table 6. Test and calculated results of masonry prisms by means of compression test

Specimen	Group A				Group B				Group C			
	Elastic modulus（MPa）	Compressive strength (MPa)		f_{mt}/f_{mc}	Elastic modulus（MPa）	Compressive strength (MPa)		f_{mt}/f_{mc}	Elastic modulus（MPa）	Compressive strength (MPa)		f_{mt}/f_{mc}
		f_{mt}	f_{mc}			f_{mt}	f_{mc}			f_{mt}	f_{mc}	
0	3876	3.92	4.02	0.96	4678	4.83	4.41	1.09	5832	5.02	4.64	1.08
1		5.24	4.02	1.30		4.20	4.41	0.95		3.69	4.64	0.80
2		3.67	4.02	0.91		3.95	4.41	0.90		4.44	4.64	0.96
3		4.09	4.02	1.02		5.29	4.41	1.20		5.70	4.64	1.23
4	3966	4.66	4.02	1.16	2456	5.71	4.41	1.29	2601	4.96	4.64	1.07
5	2756	4.17	4.02	1.04	5680	4.69	4.41	1.06	3481	4.12	4.64	0.89
6	3264	5.13	4.02	1.28	2755	4.33	4.41	0.98	6173	5.53	4.64	1.19
7	——	4.66	4.02	1.16	3268	4.98	4.41	1.13	6301	5.03	4.64	1.08
8	3341	3.31	4.02	0.82	4780	4.89	4.41	1.11	4403	4.98	4.64	1.07
9	2001	3.98	4.02	0.99	2878	4.52	4.41	1.02	4232	5.30	4.64	1.14
Average value	3200.67	4.28		1.06	3785.00	4.74		1.07	4717.57	4.88		1.05
Standard deviation	671.12	0.59		0.15	1152.36	0.50		0.11	1320.78	0.59		0.13
C.V	0.210	0.138		0.140	0.304	0.105		0.104	0.280	0.122		0.120

Note: f_{mt}: Measured compressive strength
f_{mc}: Calculated compressive strength

Table 7. Calculated results of elastic modulus and comparison with test results

Group	Average value of test results E_t (MPa)	Calculated value E_c (MPa)	E_c /E_t
A	3064	3004	0.98
B	3636	3260	0.90
C	4532	3763	0.83

Table 8. Test and calculated results of masonry prisms by means of shear test

Specimen	Group A			Group B			Group C		
	Shear strength (MPa)		f_{vt}/f_{vc}	Shear strength (MPa)		f_{vt}/f_{vc}	Shear strength (MPa)		f_{vt}/f_{vc}
	f_{vt}	f_{vc}		f_{vt}	f_{vc}		f_{vt}	f_{vc}	
0	0.143	0.116	1.23	0.163	0.140	1.16	0.172	0.153	1.12
1	0.091	0.116	0.78	0.139	0.140	0.99	0.140	0.153	0.92
2	0.095	0.116	0.82	0.169	0.140	1.21	0.173	0.153	1.13
3	0.104	0.116	0.90	0.094	0.140	0.67	0.180	0.153	1.18
4	0.120	0.116	1.03	0.142	0.140	1.01	0.148	0.153	0.97
5	0.117	0.116	1.01	0.126	0.140	0.90	0.142	0.153	0.93
6	0.133	0.116	1.15	0.170	0.140	1.21	0.166	0.153	1.08
7	0.094	0.116	0.81	0.146	0.140	1.04	0.174	0.153	1.14
8	0.084	0.116	0.72	0.155	0.140	1.11	0.118	0.153	0.77
9	0.093	0.116	0.80	0.117	0.140	0.84	0.163	0.153	1.07
10	0.125	0.116	1.08	0.132	0.140	0.94	0.153	0.153	1.00
11	0.098	0.116	0.84	0.158	0.140	1.13	0.136	0.153	0.89
12	0.139	0.116	1.20	0.099	0.140	0.71	0.189	0.153	1.24
Average value	0.11		0.95	0.14		0.99	0.16		1.03
Standard deviation	0.02		0.17	0.02		0.17	0.02		0.13
C.V	0.174		0.174	0.172		0.172	0.124		0.124

Note: f_{vt}: Measured shear strength

f_{vc}: Calculated shear strength

Table 9. Environmental impact for each 1 m^3 of concrete blocks

	GWP (kg CO_2-eq)		AP (kg SO_2-eq)		EP (kg PO_4^{3-}-eq)		HTP (kg 1,4-DCB-eq)		POCP (kg ethylene-eq)	
	R.A.	N.A.	R.A.	N.A.	R.A.	N.A.	R.A.	N.A.	R.A.	N.A.
Cement	2.84E+02	2.84E+02	7.52E-01	7.52E-01	7.80E-02	7.80E-02	7.12E-01	7.12E-01	9.86E-02	9.86E-02
NCA	7.60E-01	3.27E+00	4.58E-03	1.97E-02	7.01E-04	3.01E-03	6.60E-03	2.84E-02	4.94E-04	2.12E-03
RCA	5.10E+00	0.00E+00	1.94E-02	0.00E+00	2.78E-03	0.00E+00	2.61E-02	0.00E+00	2.16E-03	0.00E+00
Sand	1.79E+00	1.79E+00	1.49E-02	1.49E-02	1.47E-03	1.47E-03	1.42E-02	1.42E-02	8.13E-04	8.13E-04
Transportation	1.35E+01	3.34E+01	1.71E-01	4.16E-01	2.90E-02	6.94E-02	2.76E-01	6.66E-01	5.55E-02	1.70E-01
Block Production	2.13E+00	2.13E+00	2.89E-01	2.89E-01	7.30E-03	7.30E-03	9.18E-02	9.18E-02	1.72E-02	1.72E-02
Total	3.07E+02	3.24E+02	1.25E+00	1.49E+00	1.19E-01	1.59E-01	1.13E+00	1.51E+00	1.75E-01	2.89E-01

Note: Transport of NAC: Quarry to Concrete block plant-1000 km. (Rail)

Tran sport of RAC: Demolished site to Concrete block plant-20 km. (Truck_18t)

Transport of Sand: Plant to Concrete block plant-50 km. (Truck_18t)

Transport of Cement: Plant to Concrete block plant-50 km. (Truck_18t)