FIBRE REINFORCED CONCRETE ENTIRELY MADE FROM RECYCLED CONSTRUCTION WASTE, SYNTHETIC FIBRES, CEMENT AND WATER AND ITS PRACTICAL UTILISATION

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Summary: Utilisation of construction and demolition waste in production of structural concretes is still questionable. Use of fibres for enhancement of material properties and rejection of uncertainties is a hopeful solution for use of the recycled materials as aggregate in concrete. The paper will introduce possibilities of combination of fibres and waste aggregate and examples of its use in practical applications. Complex approach to utilisation of construction waste is an interesting offer for building industry contactors. Procedure of production of fibre reinforced concrete with recycled aggregate and proposed manners of manufacturing for some structural applications will be presented. Results of experiments will be shown and way of testing will be discussed for particular applications. The economical benefits and cost effectiveness will be evaluated for particular practical applications.

1 INTRODUCTION

A related phenomenon are growing volumes of piling up waste of various origin, and, in this respect, the building industry is one of the largest consumers of raw materials and energies (building industry consumes about 40% of energy and creates ca 40% of the total amount of man-generated waste). The demolition of concrete structures produces waste that is difficult to store owing to the lack of proper dumping places and high transportation and storage costs. One of the friendliest ways of managing the volumes of piling up waste which does not impose a very high burden on the environment is the exploitation of recycled and recyclable materials.

There is the potential to recycle many elements of construction waste. The scope of potential reuse of raw materials into new products is very wide and we may say that having mastered the waste processing technology, up to a 100% return rate of used material into new production may theoretically be achieved. Recycling has multiple benefits for many areas of the economy – providing raw materials, creating jobs and encouraging business opportunities and innovation too. These economic benefits of recycling are examined in a new report from the European Environment Agency. The report considers the recycling industry in the context of building a 'green economy', a major European policy objective.

This contribution deals with fibre reinforced concrete made of recycled masonry or concrete aggregate, which substitutes fully the natural aggregate in terms of its characteristics. Examples of possible application are also presented. Combination of recyclable building waste, synthetic fibres and binder yields a novel composite material with limited, but well utilizable properties for building structures. The application of this composite material is ensured by the synthetic fibres, which along with the other components constitutes the tough structure of the composite favourable especially under tensile loading due to its high ductility. The goal of the presented article is to sum up the findings and results of experimental research focused on monitoring the physical – mechanical properties of
cement composites with fibres and significant proportions of recycled aggregates. The research included the verification of achievable characteristics of a composite in which natural aggregates had been replaced with brick (masonry) or concrete recyclate. The analysis was to verify the effect of individual components on the characteristics of resulting new concrete.

2 CURRENT RECYCLING RATE IN EU AND CZECH REPUBLIC

Data on total construction and demolition waste in EU countries files The European Environment Agency (EEA). According to data published by this agency was in 2006/2007 generated about 971 million tonnes of the construction and demolition waste including soil (for 18 countries). Of this amount was currently achieved recycling or reuse rate 518 million tonnes (54%). The generation of construction and demolition waste, 32 % of Europe's total waste (EAA 2010), is closely related to economic activity in the construction sector. This waste consists mainly of inert materials such as bricks, tiles, asphalt, concrete, and to a lower extent others such as wood, plastics and metals, resulting generally in comparably low impacts on the environment per tonne of waste. However, construction and demolition waste is relevant because of its large quantity.

National data shows that in 16 out of 20 EU and EFTA countries, construction and demolition waste amounts increased between 1995 and 2006 but again with large differences between countries. The recent economic downturn is likely to have reduced the generation of construction and demolition waste but data is not yet available [1].

According to information given by the European Statistical Office EUROSTAT 48 % of the waste produced fall to construction and demolition work and further 15 % of the waste produced come from mining and stone and earth extraction in the 15 EU states.

The EU Commission Environment Committee of the European Parliament estimates that so far only 50 % of the 300 to 700 million tons of mineral construction and demolition waste produced throughout Europe a year are recycled. It is the target of the EU (The new Waste Framework Directive 2008) to achieve a recycling rate of at least 70 % for building and demolition waste (without soil and stone), to be met by 2020. The high recycling level for construction and demolition waste means that many virgin resources are saved. It can be assumed that the majority of the recovered products are recycled aggregates that replace virgin aggregates. The average annual use of aggregates is 7 tonnes per capita (EEA, 2008), and it is estimated that only around 7 % or about 250 million tonnes of the total used in 2006 were recycled aggregates (ETC/SCP,2009), indicating considerable room for improvement [2].

The development of waste generation in the EU depends largely on economic development, consumption, structural changes and resource efficiency, especially in the industrial production, construction and demolition and mining and quarrying sectors which together account for 70 % of all waste generated. For all these reasons a fast reorganization of the European economy in the sense of a recycling economy will be indispensable and is a declared aim of the European Union [1].

In Czech Republic dealt with this waste the “Association for development of recycling of building materials” (ARSM). The current recycling rate in the Czech Republic is still way behind the urgency of this problem. Like in the other EU countries, construction and demolition waste in our country also accounts for one quarter to one third of all waste production by weight. The actual state is very difficult to determine. The Evaluation of the state of waste management in the Czech Republic provides The Czech Information Agency of the Environment (CENIA) for Ministry of the Environment in database ISOH. According the ARSM are the dates of construction and demolition waste presented by CENIA only 50% actually production of this waste.

It is clear that the main volumes of CDW are brick and concrete debris (Table 1) [Source: ARSM]. There are circa 150 recycling plants in the Czech Republic which process demolition waste.
Table 1: CDW processed in recycling line in CR [3]  
(The amount in thousand of tones)

<table>
<thead>
<tr>
<th>Recycling waste</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1999</td>
</tr>
<tr>
<td>Masonry</td>
<td>488</td>
</tr>
<tr>
<td>Concrete</td>
<td>467</td>
</tr>
<tr>
<td>Asphalt</td>
<td>248</td>
</tr>
<tr>
<td>Mixed waste</td>
<td>166</td>
</tr>
<tr>
<td>Aggregates</td>
<td>477</td>
</tr>
<tr>
<td>Spoil</td>
<td>104</td>
</tr>
</tbody>
</table>

3 MASONRY AND CONCRETE RUBBLE

In many countries, including Czech Republic, recycled concrete aggregates have been proven to be practical for low-strength concretes and to a limited extent for some structural grade concrete. The processing and quality control cost associated with their use plus the price paid for mix design adjustment to achieve the same strength grade as concrete with natural aggregates can vary considerably. Aggregates from selected materials and industrial by-products, on the other hand, have great potential for use in concrete and/or as road construction materials. Recycled aggregate concrete as new concrete is produced often with combination of virgin aggregate. The use of recycled masonry aggregate for new concrete is very limited.

The recycled aggregates may be either fine recycled or coarse recycled aggregate which are obtained by crushing the construction and demolition waste. Recycling of construction and demolition waste is a relatively simple process which is based on quality recycled sorting (removing of unsuitable materials as plastic, wood, steel, glass) (fig. 1). The denominator is to start with clean; quality rubble in order to meet design criteria easily and ultimately yield a quality product that will go into end use. The more care that is put into the quality, the better product you will receive. The choice of one or several types of these recycle plants will be determined by the project. There are mobile or portable recycle plants.

![Fig. 1 Recycling process in basic steps](image-url)
Recyclate containing solely crushed concrete (at least by 90%) coming from building structures and structural members is called recycled concrete aggregates, concrete recyclate or concrete rubble. Very useful recyclate is obtained from demolitions of concrete roads and motorways or railway sleepers where high-quality concretes of higher strength classes had been used. Similar to that is with masonry materials.

Open literature commonly recommends the application of ca 30% of recyclate as substitution for natural aggregates. Many studies have proved that with this amount the properties of concrete are maintained at an acceptable quality level, often without any significant differences against concrete with natural aggregates. It is commonly used as filler into bitumen mixes, backfills or as base material in road construction.

4 USE OF RECYCLED RUBBLE IN FIBRE REINFORCED CONCRETE

One of new possibilities is the exploitation of masonry recyclate in the production of structural fibre reinforced concrete [3-9]. Fibres help to strengthen the structure of concrete with masonry recyclate enhancing, above all, the tensile characteristics of the resulting fibre concrete thus extending its application potential.

This composite may be suitable mainly for newly built road and water management earth structures with a limited appearance and occurrence of cracks (e.g. consolidation of slopes, embankments, dam crest trenches) and also for road pavement layers, layers of industrial floors and multipurpose halls, for the construction of diverse utility services, parking places, sports grounds etc. [10].

The general procedure of testing of composites mostly follows the economic criteria (cost minimization) with respect to simplicity of technology and possible applicability in practice, which would contribute to the building sustainability.

5 EXPERIMENTAL PART

The experimental programme dealt with the verification of selected material characteristics of the composite relevant for presumed applications. To obtain a wide scope of results, more potential alternative versions of mixes with different amounts of binder, different water/cement ratios and different types and amounts of fibres were produced to assess achievable characteristics of the composite. The results of the experimental programme were continuously published in [3-9].

The experiments included the production and subsequent testing of concrete in which aggregates had been fully substituted by masonry or concrete recyclates. The key parts of the fibre concrete mix are the basic components: aggregates – recyclate, cement, water and fibres. Their specific ratios and the properties of individual components principally affect the resulting behaviour of fresh fibre concrete and the characteristics of the final product.

Due to the demand for minimizing the price of the composite, the formulas were modified so that no extra admixtures or additives improving the characteristics of concretes would be necessary while preserving sufficient workability.

A series of laboratory trials were carried out to establish the practical viability of using C&DW material as replacement for virgin aggregates in fibre reinforced concrete.

6 MIXTURE DESIGNS

The experimental programme produced a wide scope of results [3-9] pointing out the achievable properties and behaviour of fibre reinforced concretes with recyclates - masonry or concrete debris.

The mix composition is based on the following principles:

- recycled aggregate of wide grading curve (a single grade, e.g. 0/32 mm or 0/16 mm),
- constant-minimum amount of binder (cement)
- weight of fibres according to the requirement of fibre concrete properties,
amount of water according to required workability. Recycled aggregates consisted in 100% content of natural aggregates. For experimental test was used unclean brick (masonry) and concrete rubble shattered in recycling plants. Properties of tested concrete and masonry rubble are shown in Table 2.

Table 2 Properties of concrete and masonry rubble

<table>
<thead>
<tr>
<th>Properties</th>
<th>Concrete rubble</th>
<th>Masonry rubble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction [mm]</td>
<td>0/32</td>
<td>0/32</td>
</tr>
<tr>
<td>Unit weight [kg/m³]</td>
<td>2439</td>
<td>2232</td>
</tr>
<tr>
<td>Loose unit weight [kg/m³]</td>
<td>1391</td>
<td>1133</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>35.4</td>
<td>40.0</td>
</tr>
<tr>
<td>Fineness modulus [-]</td>
<td>4.67</td>
<td>5.04</td>
</tr>
<tr>
<td>Water absorption [%]</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Unclean masonry and concrete rubble were shattered in recycling company. The advantage of the wide grading curve of the used recycled aggregate is apparent in the design of fibre concrete (0/32 mm). The recycled aggregate graded according to this limitation can be characterized as to be of the so-called wide grading curve.

In a mixture proportion the amount of cement was given on minimum for structural concrete according to Code EN 206-1 (260 kg/m³). The amount of water should be decided according to workability requirements. Values of water-cement ratio of the mixture was between 0.5 - 0.6.

Specimens were made with made of 100% virgin copolymer/polypropylene fibres FORTA FERRO®. FORTA-FERRO® is used to reduce plastic and hardened concrete shrinkage, improve impact strength, and increase fatigue resistance and concrete toughness. These fibres are non-corrosive and 100% alkali proof. In order to minimize cost an optimal dosage of polypropylene fibres was determined as 0.5% and 1% by volume concrete content added directly to the concrete mixing system during the batching of the other ingredients. The fibres are 54 mm in length and their tensile strength is 570-660 MPa. Their specific gravity is 910 kg/m³. The data record of tensile test of fibre FORTA FERRO® is shows in fig. 2. Tensile tests were performed on testing machine FP 10/1 with a max. load 10 kN with test speed 5 mm/min.
1.5% of volume content. As it is known, the final properties of FRC composition are influenced by the type and origin of the fibre, its parameters and used dosages. Influence of fibres is characterized by higher ductility, toughness and their higher bearing capacity after first crack appearance.

Second used fibres BeneSteel are made from the mix polypropylene and polyethylene with tensile strength about 610 MPa and modulus of elasticity about 5170 MPa. Fibre diameter is 0.48 mm. These polymer fibres are used for construction fibre reinforced concrete.

Fibres cut from waste PET bottles (Fig. 3) are alternative for a price reduction of fibre concrete and contribute to solution of PET waste problems too. Applicable are fibres with length 60-110 mm depending on maximal size of aggregate. Width of this fibre was tested 0.7-2.5 mm. Thickness of fibres is 0.25-0.28 mm. Tensile strength of fibres cut from waste PET bottles is 80-140 MPa (Fig. 4). Tests were performed on the tensile equipment FP 10 / 1 with a maximum force of 10 kN, crosshead speed of 5 mm/min.

![Fig.3 Tensile test of fibre FORTA](image)

![Fig.4 Tensile test of fibre from PET (width of fibre 2.3 mm)](image)

7 RESULTS OF EXPERIMENTAL PROGRAMME

The fibre reinforced concrete with the recycled aggregate has sufficient characteristic for selected applications [6]. On the basis of realised experimental tests we can say that:

1. Fibre concrete is porous and thus it is not water-resisting.
2. The pores and gaps contribute to the interaction with the surrounding earth, with increases the effect of the inserted slabs in the case of earth structures.

3. The porous structure of the composite allows higher ductility in tension under the condition, when the dispersed synthetic fibres are anchored with the hydrated cement paste to the recycled aggregate.

In the following table 3 are show the selected results of extensive experiments. Basic mechanical-physical properties as initial bulk densities, compressive strengths, flexural strengths and tensile-splitting strengths, pseudo-working diagram force – deflection, modulus of elasticity are determined.

The basic mechanical properties in tension of the tested fibre reinforced concrete (Fig. 5) can be derived according to [8]. The measurement of properties was performed according to standard test methods the Standard ČSN EN. Series of mechanical-physical experiments were carried out with beams of the valid standard dimension 150 x 150 x 150 mm and 150x150 x 700 mm. The specimens were tested after 28 days after mixing.

Tab. 3 Selected results mechanical-physical properties of fibre concrete

<table>
<thead>
<tr>
<th>Samples</th>
<th>Recycled aggregate</th>
<th>Type of fibres</th>
<th>Volume of fibres [%]</th>
<th>Bulk density [kg/m³]</th>
<th>Compressive strength [MPa]</th>
<th>Tensile-splitting strength [MPa]</th>
<th>Modulus of elasticity [MPa]</th>
<th>Flexural strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM1</td>
<td>MR</td>
<td>FF</td>
<td>0.5 %</td>
<td>2041</td>
<td>21.97</td>
<td>2.22</td>
<td>14.7</td>
<td>1.85</td>
</tr>
<tr>
<td>FM2</td>
<td>MR</td>
<td>FF</td>
<td>1.0 %</td>
<td>1842</td>
<td>19.11</td>
<td>1.82</td>
<td>13.6</td>
<td>2.44</td>
</tr>
<tr>
<td>FC1</td>
<td>CR</td>
<td>FF</td>
<td>0.5 %</td>
<td>2099</td>
<td>13.75</td>
<td>1.69</td>
<td>14.6</td>
<td>2.09</td>
</tr>
<tr>
<td>FC2</td>
<td>CR</td>
<td>FF</td>
<td>1.0 %</td>
<td>2084</td>
<td>13.83</td>
<td>1.71</td>
<td>15.3</td>
<td>2.16</td>
</tr>
<tr>
<td>PM1</td>
<td>MR</td>
<td>PET</td>
<td>1.0 %</td>
<td>2104</td>
<td>19.55</td>
<td>2.38</td>
<td>-</td>
<td>1.95</td>
</tr>
<tr>
<td>PC1</td>
<td>CR</td>
<td>PET</td>
<td>1.5 %</td>
<td>2080</td>
<td>28.67</td>
<td>3.07</td>
<td>-</td>
<td>1.97</td>
</tr>
<tr>
<td>PM2</td>
<td>MR</td>
<td>PET</td>
<td>1.0 %</td>
<td>2104</td>
<td>19.55</td>
<td>2.38</td>
<td>-</td>
<td>1.95</td>
</tr>
<tr>
<td>BM1</td>
<td>MR</td>
<td>Benesteel</td>
<td>1.0 %</td>
<td>2052</td>
<td>17.32</td>
<td>1.78</td>
<td>-</td>
<td>1.98</td>
</tr>
<tr>
<td>BC1</td>
<td>CR</td>
<td>Benesteel</td>
<td>1.0 %</td>
<td>2028</td>
<td>26.96</td>
<td>2.62</td>
<td>-</td>
<td>2.74</td>
</tr>
</tbody>
</table>

(F – Forta Ferro fibres, P – PET fibres, B – Benesteel fibres, C (CR) – concrete rubble, M (MR) – masonry rubble)

For the characterization of the post-cracking behaviour of fibre reinforced concrete are recommended the evaluation of the equivalent flexural tensile strength parameters. The specimen geometry, the method for casting the specimens, the curing procedures, the loading and specimen support conditions, the characteristics for both the equipment and measuring devices and the test procedures recommended by TP FC 1-1 [show in 11]. The test is based on four point bending test using for plain concrete. Specimens are the prisms with recommended size 150 x 150 x 700 mm.
8 APPLICATIONS OF THE COMPOSITE

Several areas of application have been recognized however full-scale use of such fiber reinforced concrete is still hindered by the high cost, which is unacceptable for investors. The examples of application of such fiber concrete, which would help to meaningfully utilize the demolition waste, are so far based on numerical simulations and developed laboratory models.

Based on the experiences gathered during experiments, which focused on determination of mechanic-physical properties of this composite, the possible applications are:

- reinforcing layers (slabs) in earth structures (e.g. road and railway embankment),
- flood-resistant dikes and water reservoir dams.

The fibre reinforced concrete slabs can be placed in the earth structures which increase their slenderness and thus contribute to reduction of the volume of earth work. Another example of possible application, which is the current topic of research, is reinforcement of earth-fill dams, which extends the operating lifetime in the case of overspill during floods. When the high water spills over the dam crest, the dam can be subjected to the surface erosion. The inserted fibre concrete slabs in the earth-fill dams also in this case contribute to the stability and slenderness of the structures. Another advantage can be seen in the anchoring of the anti-erosion mats or reinforced geosynthetics to the FRC concrete slabs. The exact thickness, the distance and location of the layers depends on the specific application (or structure) and optimization of the design, and always it will be the result of static check of the tackled structure.

More information about the experimental programme with goal to demonstrate the effects of inserted FRC slabs in earth structures are presented in [10]. The effects of inserted slabs on stability limit state in the shear zone has been investigated using numerical simulation and in real material model. The savings in terms of smaller cross section of the embankment can be considered significant, which can be seen in Fig. 5.
Fig. 5 Example of earth structures with inserted fibre reinforced concrete slabs

Fig. 6 shows the original state of a test dam and its state after overspill. It is apparent that the inserted slabs change the progressing damage due to overspill considerably. The test with longer period of overspill showed that the damage reached a limit and thus the dam with inserted slabs proved serviceable in the long-term scope.

Fig. 6 Model of earth-fill dam demonstrating stability of dam after overspill

9 CONCLUSIONS

This work as thesis aims to reduce the demand for primary aggregates by using crushed C&DW as an alternative. The addition of an optimal dosage of polypropylene fibres or fibres cut from waste PET bottles changes the properties of concretes and so provides new possibilities for using recycled concrete especially in transportation engineering.

Based on a large series of acquired experimental results on different characteristics of the tested material, it can be judged on the behaviour of this composite. The completed experimental programme contributes to extending knowledge in using recyclates for the production of concrete and for setting the limits of achievable properties. The previous experimental program has proved that the properties of this concrete are sufficient enough to be used in ground structures as intended. With depleting natural resources new possibilities must be sought for the substitution of natural aggregates, where, thanks to its properties, brick or concrete recyclate represents a suitable alternative solution.
The most effective way to reduce the waste problem in construction is agreed in implementing reuse, recycling and reduced the use of a construction material in construction activities. Those “3R” are the positive influence on Economy, Ecology and Energy.

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