Fibre reinforced concrete with recycled concrete aggregate – inverse design approach

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Abstract. The paper aims at the topic of sustainable building concerning recycling of waste rubble concrete from demolition. The objective of the presented investigations was to verify the proposed breakthrough approach to utilisation of crushed waste concrete in construction of various types of structures. The traditional philosophy of the designing procedure – to find a suitable material for a given structure – is transformed into a new way of designing entitled “inverse design approach” that intends to find a suitable structure for a low-strength porous composite material that is obtained from available recycled rubble concrete. In the first stage, composition of concrete mix optimal from the point of view of mechanical properties, workability and economy is estimated based on the experience of the authors. The keynote is maximising of recycled aggregate use, minimising of cement consumption and providing competitive advantage of the composite made from concrete waste. Properties of the material are determined in laboratory tests. Possible applications of the composite in the construction industry are proposed. Finally, one of the possibilities is selected for verification. The results have shown that the introduced inverse design approach is applicable; it can lead to exploitation of significant amounts of construction waste in a useful way, to substantial savings of primary resources and to reduction of carbon footprint of the construction process.

1. Introduction
Growing demand for cutting carbon emissions, reduction of pollution emitted from building industry, saving natural resources and raw materials should target to reduction of construction waste disposal in landfills, re-use of construction materials, utilization of non-traditional materials or non-traditional use of common materials. Utilization of recycled materials is one of European Community priorities. The 7th Environmental Action Programme for Europe promotes increase of recycling and re-use of materials. In accordance with these requirements, utilization of the secondary raw materials is investigated, such as recycled concrete.

The construction and demolition waste constitutes a quarter of all types of waste production. Reuse of this waste in other areas of the economy is a step in the right direction to achieve sustainable development. Research and development institutes contribute to the topic of sustainable construction by research of recycled materials. One of the focuses is on replacing of natural aggregate by rubble concrete recycled from demolished concrete structures.

Use of RCA (recycled concrete aggregate) in concrete is restricted by code prescriptions on aggregate testing, quality of aggregate and limits of maximal amount of recycled aggregate which can
be used as a substitution of natural aggregate. The restrictions are caused by the reason of worse quality and high dispersion of recycled aggregate characteristics, which are commonly known.

Background of our research was a challenge to overcome the limitations, benefit from features of the material and tribute to wider application of wastes. One of the objectives was to reduce testing of recycled aggregate in the process of manufacturing concrete composite and the attention focus on properties of the composite.

The purpose and target of our aspirations was to change the understanding in attempts to apply RCA in concrete; it should not be regarded that RCA is used to make concrete with downgraded properties compared to common concrete. Under a new perspective RCA is used to make a new composite, which is relevant in certain applications.

2. State of the art in the field of utilisation of recycled concrete

History of recycling of construction and demolition waste and reuse of materials dates back to ancient times. Modern history with comprehensive research of materials goes ahead since the fifties of the last century.

The essential characteristics of crushed concrete aggregate revealed in previous investigations are:

- downgraded material parameters compared to natural aggregate (NA),
- modified grain-size distribution, flakiness index and density,
- higher water absorption.

Many observations of particle size and shape concluded that recycled concrete aggregate (RCA) is coarser, more porous and rougher in surface but more equidimensional [1]. The density of recycled aggregate is reported to be lower than natural aggregate density [2], [3].

The biggest differences between recycled and natural aggregate are in water absorption. Common natural aggregate’s water absorption value is about 0.5 – 1 %. Recycled aggregate’s water absorption is higher due to cement paste fixed to the original natural aggregate. Studies showed water absorption of recycled aggregate ranging between 3 – 6.5 % [4].

Nowadays, most recycled concrete is used as aggregate in base and sub-base layers of new road pavements. Utilization of recycled concrete aggregate in new concrete mixtures and application for structural use is rather limited. The primary restrictive factor is contamination of the recycled aggregate by impurities, which causes deterioration of material parameters such as strength, elastic modulus etc. Removing the impurities increases production costs of the recycled aggregate concrete.

The problem of worse material parameters of recycled aggregate is commonly faced by blending of RCA and NA [5], [6]. The main factor adversely affecting the strength of concrete produced with RCA is supposed to be the residual mortar attached to the original aggregate in recycled waste concrete. Some investigations focused on removing and strengthening the adhered mortar in RCA. Methods for improving the properties of RCA are based on mechanical and chemical treatment [7], [8], [9].

Recent research works examined the properties of high performance concrete (HPC) with RCA anticipating that good-class recycled concrete with quality original aggregate (e.g. from prestressed structures) shall provide satisfactory properties of HPC with a blend of RCA and NA [10], [11]. These attempts are more theoretically focused and the mixes have been manufactured just in laboratories so far.

Large scale utilization solely of RCA (without blending of RCA and NA) is uncommon [12].

3. New approach to the composite design

Recycled aggregate accounts for ca 8% of aggregate use in the European production. Presented investigations focused on increasing of this ratio and consuming of a significant quantity of crushed concrete from construction and demolition waste (CDW) in production of recycled aggregate concrete (RAC) and minimising of natural aggregate depletion. Long term research of properties of recycled aggregate and concrete made from recycled aggregate resulted in proposal of changing the design philosophy. The keynotes of the approach are:
• maximising of recycled aggregate consumption
• minimising of environmental burden
• minimising of the production cost

In terms of these presumptions, a new concept of the composite mixture design and structural design procedure was introduced. Common concrete mix design begins by determining the requirements on concrete; required concrete class is set according to conditions that the concrete will be exposed to in service. In the new approach, the procedure of the structural design and concrete mix design is inverted, therefore the authors decided to call it “inverse design approach”. In the initial phases a mixture is specified, subsequently material properties of hardened concrete are examined and identified. According to achieved material parameters, suitable application for the material is suggested (fig. 1).

The mix recipe is based on these principles:
1. composite is made entirely with recycled aggregate;
2. aggregate from crushed concrete is used without sorting;
3. composite is made with minimal cement content;
4. admixtures and additives are not used.

The systematic investigations of the authors have proved that to meet all the above-mentioned requirements while obtaining a material with the mechanical properties sufficient for structural use, dispersed reinforcement has to be added to the mix. As a result, there are four components in the mixture: recycled concrete aggregate, cement, fibres and water.

3.1. Aggregate
The coarse and fine aggregate are represented entirely by crushed recycled concrete. Using of just the recycled aggregate (not a blend of natural and recycled aggregate) tributes to higher consumption of concrete waste, generates less landfill and decreases depletion of natural resources.

Utilisation of crushed concrete aggregate with wide particle size distribution (aggregate without sorting) will provide competitive advantage of the composite.

The unsorted crushed concrete aggregate usually contains a great deal of coarse aggregate. The void content is relatively high due to the reason that the crushed material contains a great deal of large grains. Next to higher water absorption, also the porosity of RCA is higher than the natural aggregate’s ones. The scatter of porosity is high and differs according to the source of RCA and crushing method used.

Figure 1. Flow chart of common design and inverse design approach.

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3.2. **Cement binder**
Dosage of cement relates to the economic and ecology aspects of the research. The cement dosage is specified as minimal amount required by the codes for structural concrete.

Minimal cement dosage contributes to the environmentally friendly production. Together with leaving out of admixtures and additives, it also decreases the total costs of the resulting material.

Minimal cement dosage ensures covering of aggregate with the binder. The interlocking in the composite structure is increased by fibres.

3.3. **Water**
The water absorption capacity of aggregate influences the properties of the fresh concrete such as its workability.

The dosage of mixing water depends on water absorption of recycled aggregate and aggregate moisture state. The mixing water is dosed to reach the mixture consistency convenient for compaction by ramming or tamping (vibration cannot be used because of the high porosity of composite).

3.4. **Fibres**
Fibres in the mixture strengthen the structure of the composite and provide tensile strength and toughness. Activation of fibres after macrocracking increases the ductility of the composite.

In the choice of materials for fibres, high porosity and permeability of hardened concrete should be considered. To prevent deterioration of fibres due to penetrating moisture, synthetic fibres should be selected; steel fibres in the pervious concrete are improper because of possible corrosion. Sufficient length of fibres must provide interlocking of fibres between aggregate grains and creation of consistent composite matrix. Optimal length of fibres is usually given as proportion of fibre length to aggregate grain size ranging between 2.5 and 3. Several types of fibres were investigated in the research program, e.g. polypropylene fibres, polyolefin fibres or fibres cut from PET bottles. The concern is on choice of cheap fibres, or alternatively fibres made from waste materials.

3.5. **Technology**
Dry components are weighed and mixed together with synthetic fibres. After uniform dispersion of fibres, water is added. The dosage of water is adjusted to reach adequate workability for compaction by ramming or tamping. Hardened composite has porous structure with relatively large void content.

3.6. **Testing material parameters, analyses**
In the second phase of the inversed procedure, material properties and behaviour of the composite are identified.

Strength parameters are determined in tests commonly used for testing of concrete and fibre reinforced concrete. Compressive strength is determined on 150 mm cubes. The same type of cubes is used for testing of tensile splitting strength. Flexural behaviour and stress-strain properties are examined in four-point bending tests on 150/150/700 mm prisms.

Results of the tests are the base for finding the appropriate application of the composite. They can be used in calculations or numerical simulations to decide about the applicability of the composite for a particular structure. If a potentially suitable structure is identified, laboratory experiments on structural models made of the given composite can be performed.

In certain cases supplementary test are proposed to verify other favourable properties of the composite suitable for specific application (e.g. elastic modulus, creep properties, permeability etc.).

4. **Example of the use of the inverse design approach**
The text below describes one example of the design of recycled concrete mixture in accordance with the principles described in the previous chapter. Performed tests and experiments, detected parameters and properties are summarized. In the end, possible application of the material is proposed.
4.1. Mixture composition
Recycled aggregate originated from railway sleepers (fig. 2, 3) from closed precast factory siding railway located near the recycling centre. The prestressed sleepers are commonly made of concrete with strength about 45 MPa, hence the quality of the original concrete is good. The sleepers were crushed in jaw crusher, reinforcement and fasteners were removed by crushing shears before placing the sleeper on the feeding hopper with raft sorting machine. After separation of reinforcement a coarse loose material remained without great portion of metal components. The loose material was crushed by jaw crusher with electromagnetic separator to take out the remaining metal parts.

![Concrete sleepers before crushing](image1.png)

![Recycled aggregate from the crushed sleeper](image2.png)

For practical applications, conformably with the principle of cost minimizing the recycled aggregate is used without sorting, as sorting of aggregate regarding grain size distribution increases the cost of recycled aggregate.

Nevertheless, the gradation and other RCA properties were determined for research purposes. Maximum grain size was 22 mm. Results of sieve analysis are depicted in fig. 4.

![Gradation curve of the recycled concrete aggregate](image3.png)
Each of the three samples with weight 2 kg was separated through a set of standard sieves; the weight of particles retained on each sieve was measured. Results of the sieve analysis are plotted. Grading pattern displays nearly a gap graded distribution of particles. The crushed concrete contained a great deal of coarse aggregate.

Bulk density, void content and absorbability of recycled aggregate were determined in pycnometric analysis. The void content was ca 35%. It is rather high by the reason that the crushed material contains a great deal of large grains. Absorbability was about 3.5 % which is quite a low value. Typically the absorbability of recycled aggregate is higher. The lower absorbability is given by low content of fine aggregate which provides high water absorption.

4.2. Cement binder
Type I hydraulic Portland cement was used, with 95 % of Portland cement clinker (chemical composition is in the table 1). Specific surface area of cement binder was 381 m²/kg.

Dosage of cement relates to economic and ecology aspects of the research project and it was determined with respect to the European Standard EC 206-1 requirements as the minimal cement content for structural concrete (260 kg/m³).

4.3. Fibres
This particular composite is strengthened with polymeric fibres. The fibres are made of special blend of polypropylene and polyethylene. The tensile strength is 610 MPa, the elastic modulus is 5 500 MPa. The length of fibres is 55 mm, aspect ratio 115 and density 910 kg/m³.

| Component       | Dosage [kg/m³] |
|-----------------|----------------|
| Recycled aggregate | 1 400         |
| Cement          | 260            |
| Fibres          | 9.1            |
| Water           | 150            |

Dry components were weighed and mixed for about four minutes together with the fibres. After uniform dispersion of the fibres, water was added. The dosage of water was adjusted to reach adequate workability for compaction by ramming or tamping.

After hardening, the composite had a porous structure with relatively large void content (fig. 5).

![Figure 5. Hardened fibre reinforced concrete with recycled aggregate.](image)

4.4. Testing program
In laboratory tests, parameters related to the structural function of the composite – tensile splitting, flexural and compression strengths – were determined. Common tests with 150 mm cube specimens were performed at the age 28 days to determine compressive strength and tensile splitting strength.
Table 2. Results of compression tests.

| Specimen | Dimensions of the specimen | Weight | Density | Load | Compressive strength |
|----------|-----------------------------|--------|---------|------|----------------------|
|          | width [mm] | length [mm] | height [mm] | [kg] | [kg/m³] | [kN] | [MPa] |
| A1       | 149        | 149        | 149        | 6.088 | 1840.4 | 276  | 12.43 |
| A2       | 149        | 147        | 149        | 5.946 | 1821.9 | 216  | 9.86  |
| A3       | 149        | 145        | 149        | 6.032 | 1886.5 | 350  | 16.2  |
| A4       | 149        | 149        | 149        | 6.034 | 1824.1 | 254  | 11.44 |
| A5       | 149        | 150        | 148        | 6.302 | 1905.2 | 282  | 12.62 |
| A6       | 148        | 149        | 151        | 5.98  | 1795.9 | 214  | 9.7   |
| A7       | 149        | 149        | 149        | 5.972 | 1805.3 | 208  | 9.37  |
| A8       | 149        | 150        | 148        | 6.106 | 1845.9 | 236  | 10.56 |

Average value | 1840.7 | **11.52** |
Conditional standard deviation | 35.7 | 2.11 |

Characteristic value of compressive strength was calculated from measured data according to ISO 2394. General principles on reliability of structures were taken into account using $k$–coefficient, for eight specimens $k = 2$. The characteristic strength of recycled aggregate fibre reinforced composite was $f_k = 7.3$ MPa.

Table 3. Results of tensile splitting tests.

| Specimen | 1   | 2   | 3   | Average value [MPa] | Conditional standard deviation |
|----------|-----|-----|-----|----------------------|--------------------------------|
| **Tensile splitting strength** | 0.6797 | 0.7042 | 0.7231 | **0.702** | 0.02 |

Figure 6. Load deflection diagram from four-point bending test of fibre reinforced composite with recycled aggregate on 100/100/400 mm prism.
The most efficient tests to describe the behaviour of the composites with dispersed fibre reinforcement are flexural tests. Four four-point bending test set-up was applied on 100/100/400 mm specimens. Load-deflection curves are depicted in figure 6.

Compressive strength is lower than strength of common concretes as anticipated; the tensile properties and ductility are acceptable and comparable to dense concrete.

High porosity of the composite led to the assumption of efficacious thermal properties. Volumetric thermal capacity and thermal conductivity were measured.

| Specimen | thermal conductivity $\lambda$ [W/mK] | volumetric heat capacity $c$ [$10^6$ J/m$^3$K] |
|----------|-------------------------------------|--------------------------------------|
| 1        | 0.6741                              | 1.4244                               |
| 2        | 0.7505                              | 1.5288                               |
| 3        | 0.5892                              | 1.3925                               |
| 4        | 0.7689                              | 1.5213                               |
| 5        | 0.6005                              | 1.4068                               |
| 6        | 0.5926                              | 1.4083                               |
| Mean value | 0.663                          | 1.447                                |
| Standard deviation | 0.082                      | 0.061                                |

Thermal conductivity of the developed porous composite is comparable to conductivity of concretes with lightweight aggregate (e.g. expanded clay, typically 0.3 – 0.8 W/mK) and less than thermal conductivity of dense concrete and solid brick masonry (usually about 1.4 W/mK). The volumetric heat capacity is lower than the volumetric heat capacity of dense and lightweight concrete and solid brick masonry. The potential of thermal benefits of the composite was proved.

4.5. Composite application
To select an appropriate application of the composite, strength and thermal properties were considered. In the end, wall structures were selected as the most prospective option. To verify this possibility, laboratory tests with compressed members were executed. Two non-standard types of prism specimens with dimensions 150/150/600 mm and 150/150/1200 were loaded with given eccentricity in the direction of their axis and their behaviour was also modelled in numerical simulation (fig. 7).

Results of these tests and simulations were satisfactory and proved sufficient resistance for combination of compression and bending. Subsequent probabilistic analysis revealed problems given by relatively high scatter of material characteristics which implies low characteristic value of strength and high material safety factor. Hence the resistance of the structure is adequate just for very low loading. For application of the material in load-bearing walls, the material characteristics would have to be homogenized and the dispersion of material parameters decreased. Results of tests and related analyses were presented in [13] and [14].

The thermal properties of the material are favourable and application in non-loadbearing walls is prospective. There are two potential forms of application in the wall structure – in-situ variant (composite compacted by ramming in the formwork) and masonry units or hollow blocks made of the composite.
Figure 7. Comparison of load – deflection diagram of the specimen 150/150/600 mm recorded in compression laboratory test (full line in red) and load – deflection diagram calculated in numerical simulation of the test (dashed line in blue).

5. Further examples of possible applications of the composite

The target in the development of the new composite was not an effort to copy or imitate existing material but to find a new material and according to its properties and behaviour propose an appropriate application.

A number of mixes with various combinations of aggregate (of different sources and with different way of crushing), fibres (common fibres available on the market and alternative fibres, e.g. fibres cut from plastic bottles) and binders (various types of cement or blend of cement and alternative binders) were inquired into and examined. Material characteristics obtained for particular mixes – porosity, strengths characteristics, ductility, thermal and acoustic properties – were considered according to principles of inverse design approach. This section presents examples of proposed applications for several types of composite:

- sub-layer in pavements, roadways, parking areas, sport grounds;
- stabilizing layers in earth bodies;
- strengthening layers in earthen dams;
- noise barriers.

Particular applications were assessed concerning technical feasibility. Computational models were developed and numerical simulations performed, for some types of applications loading was performed on scale models.

5.1. Fibre reinforced composite from RCA in sub-layers

The composite can be efficiently used for stabilizing layers in pavements, cycle routes, roadways, parking areas and sport grounds. This application takes the advantage of permeability of the composite that will tribute to draining of sub-layers in these types of structures. Technology of the composite compacting complies with the road and pavements construction technology of roller compacting. Vast amounts of material are consumed in sub-layers, thus a big portion of waste material will be utilised and not deposited in the waste landfills.
5.2. Fibre reinforced composite from RCA in earthworks
Use of the composite as a strengthening layer in earthworks benefits from tensile strength, ductility and permeability of the composite. The pervious layer allows water from precipitation to pass through, prevents runoff and contributes to groundwater recharge.

Numerical simulations showed that stabilizing FRC layers in the earthen body enable to increase the steepness of the slope and thus to decrease farmland occupation (Hruby, 2011).

Numerical simulation of 15 m high embankment with three stabilizing layers confirmed that sloping can be steeper by 11 degrees or narrower by 10 meters compared to un-stiffened earth body. The reduction of the embankment width by 2x10 m determined in the studied case would bring significant savings. Considering the purchasing price of farmland in the Czech Republic as 1 €/m², saving of 20x1x1000 = 20 000 € per one kilometre of the dam can be estimated. The savings can be even much higher in case that the structure is built on a more expensive estate such as forest or building land.

5.3. Fibre reinforced composite from RCA in earthen flood dams
Fibre reinforced composite with recycled aggregate can be utilized for stabilizing layers in earthen flood dams.

This application was proposed for recycled aggregate that incorporated higher amount of fine aggregate and the porosity of resulting composite was lower.

To prove the benefits of the stiffening composite layers, two laboratory models in scale 1:30 were prepared. The first model of dam was made entirely from soil; the stiffening layer was only used at the dam crest to prevent damage of the crest in case of overflow and to enable observing of the erosion of the downstream side of the dam.

The other model contained three more stiffening layers except the one in the crest (fig. 8, 9).

![Figure 8](image)

Figure 8. Model of the dam stiffened with four stiffening layers made of fibre reinforced composite with recycled aggregate (dimensioning in mm).

The experimental small-scale models proved benefits of the stiffening layers from fibre reinforced composite with recycled aggregate in case of overtopping of the dam.
5.4. Noise barriers
Porous materials are generally exploited as sound absorbing materials. On the premise that sound energy will be dissipated in a series of interconnected cavities in the porous fibre reinforced composite with recycled aggregate is based next proposed application in the noise barrier. The assumption must be verified by laboratory test. Sound absorbing coefficient must be determined and reduction of sound pressure level must be verified for particular frequencies. [15]

6. Conclusions
The paper introduced a new approach to the design of cementitious composites with recycled aggregate content – so called “inverse design approach” – that enables to maximize the exploitation of secondary aggregates in concrete for structural applications. The applicability and possible benefits of this approach were demonstrated on several examples.

The inverse design approach is based on the idea that for each recycled concrete mix, an application that will gain the highest profit from the properties of the particular material should be selected. The whole method is therefore in accordance with the principles of the sustainable development which is conditioned by the effective use of the resources. The advantages of the “inverse design approach” include also simplification of the composite manufacturing; as the recycled aggregate is used without sorting and other additional treatment. The main benefit is changing the perspective and offering alternative view of designing cement composites from RCA – it should not be regarded that RCA is used to make concrete with downgraded properties compared to common concrete. In the proposed approach RCA is used to make a new composite, which is relevant in certain applications.

Certainly the limitations must be considered, too. The input material – recycled concrete aggregate possesses heterogeneous properties, what affects the scatter of resulting composite characteristics. The manufactured composite is a porous low-strength material with higher dispersion of material parameters, what must be considered in the choice of appropriate application.

The resistance, safety and the economic aspects still play the main role in the decision-making process when the construction material for the planned structure is selected. However, new aspects of the designing process such as environmental issues and depletion of natural resources are becoming...
more and more important. Increased utilization of recycled concrete contributes to saving of raw materials, elimination of the need for disposal of construction waste and low carbon production.

Acknowledgments
This paper has been prepared with the financial support of the Technology Agency of the Czech Republic within the project TH02030649 EESDOK – Environmentally Efficient Construction and Demolition Waste for Structures and the Ministry of Education, Youth and Sports, project: Durability of concrete structure and assessment of its life cycle, SGS19/149/OHK1/3T/11.

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