SIMULATION OF BEHAVIOUR OF FRC WITH RECYCLED AGGREGATE


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Summary

Application of recycled materials in the building industry is important for sustainable development of a country. In the Czech Republic, the use of primary sources and materials is becoming unbearable from both the economical and ecological perspective and so there is an effort to seek the possibility in re-use of those building materials whose live-span has been exceeded. At present, the mostly recycled materials in the Czech Republic come from the recycled waste of bricks, concrete, asphalt, mixed building waste, various types of aggregates and soil. This contribution brings the recent results devoted to reinforcing of concrete made of recycled concrete aggregate with dispersed fibres.

The experience was gained from experiments within research cooperation with industrial companies which are involved in production of fibre concrete members. Recycled building materials are tested for future use as ordinary building materials and prospects and willingness to use recycled building materials. A part of the contribution is devoted to strengthening of concrete made of recycled masonry aggregate with dispersed synthetic polypropylene fibres, which is now being developed in our department.

Keywords: Recycled concrete, steel and synthetic polypropylene fibres, recycled aggregate, recycled concrete, structural analysis, simulation of behaviour

1 Introduction

Recycling of construction materials is growing, along with the demand for recycled materials. Recycling of building waste as an independent branch in the building industry started in the Czech Republic in the 90´s by introduction of first crushing and screening machines developed for that purpose. During the first years, the construction companies did not show any interest in the seemingly unreliable second-class aggregate and so the recycled materials were distributed for free. Even then most of the recycled aggregated was headed to dumping grounds.

However, growth in the use of recycled materials is often constrained by insufficient knowledge of material performance, low awareness of benefits and perceived risks.

Concrete with aggregate from recycled materials, which enables saving sources of natural aggregate, is considered to have generally worse mechanical properties than common concrete. But the idea to add fibres to a concrete mixture with recycled aggregate may change material properties of such concrete, improve behaviour and bring about new types of applications. Fibre reinforced concrete with recycled aggregate can be considered as optimal structural concrete for various applications.

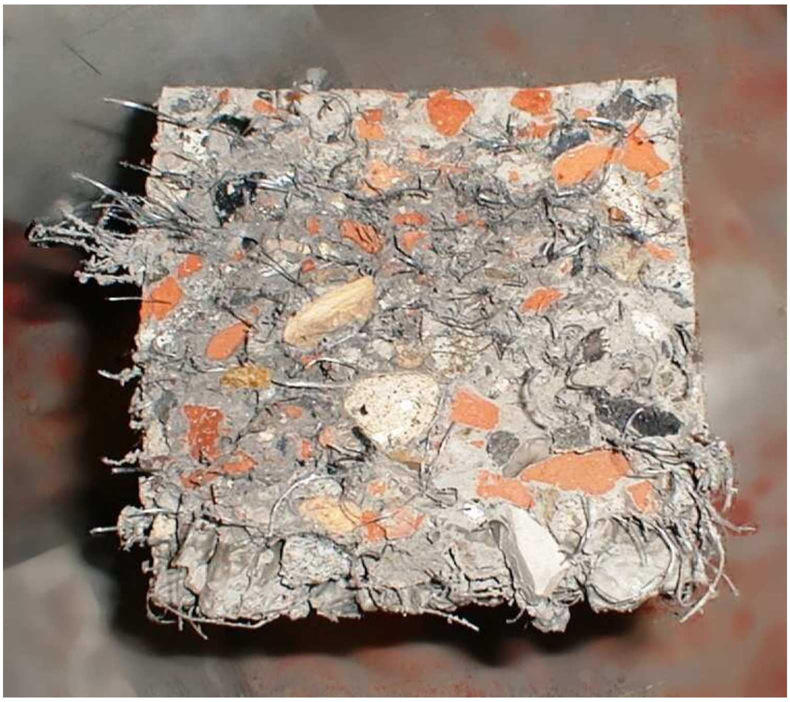

Fig. 1 Specimen with recycled aggregate and synthetic fibres after testing in the laboratory

2 Possibilities of analysis of member cast from concrete with recycled aggregate and fibres

The tests showed that behaviour of the material reinforced with fibres changed significantly. Member cast from mixture with dispersed fibres has more ductile behaviour compared to relatively brittle mode of failure of members without fibres. To take benefit of the fact the positive behaviour shall be involved in the structural analysis. An efficacious design approach should ideally consist of a methodology of experimental determination and interpretation of material properties, formulas or steps used in the design of the element or structure, and an indication of the limitations and reliability of the approach.

In reality, however, most of structural designs are based on empirically-obtained code equations that are loosely based on elasticity or plasticity theories and/or on experience-based serviceability criteria. Some of these approaches do not involve advantageous structural behaviour of fibreconcrete element as the residual tensile strength and ductile behaviour is involved in the analysis just partially and simply. A strong tool for congenial analysis that involves all benefits of fibreconcrete member is a finite element simulation.

Behaviour of the structure under service as well as ultimate conditions can be virtually simulated using computer methods quite realistically. Nonlinear analysis that exploits fracture mechanics and assumes higher fracture energy of FRC and the different form of the tensile constitutive law enables to exploit reserves, which are usually neglected or diminished in codes or in linear analysis. Therefore, special material models at macroscopic level are needed for modelling of FRC-material in the numerical simulation of FRC-based structures.

3 Formulation of material law in FEA

A fundamental step in a structural design is a determination of material properties. Conventional procedures are normally based on the stress-strain (σ-ε) response of the materials across the critical section. Along the lines of such σ-ε approaches, the models for the behaviour of FRC have replaced those for plain concrete in the design of fibre concrete structures and the tensile response of the concrete is taken into account, instead of being neglected. A step further is the use of toughness-based limit stresses that draw on the improvement in the ductility of the concrete due to the incorporation of fibres. On the other hand, the use of the fracture response or the stress versus crack opening or width (σ-w) response of FRC has led to more general approaches for cross-section design. Such approaches also implicitly account for size and geometry effects that often create problems in conventional limit stress or strain based design. Moreover, it is also easy to incorporate structural defects in such analysis (in the form of notches) to study failure modes and ultimate limits. In the FE simulation the main aim is to find a stress-strain (σ-ε) or stress-CMOD (σ-w) relationship that works with the method of FEA.

For fibreconcretes a list of material properties known from concrete design is not available because fibre-reinforced concrete material properties strongly depend on the fibre type, i.e. material of fibres, fibre cross-section, aspect ratio (fibre length to fibre diameter) and the amount of fibres in concrete mixture. Therefore a simple routine of determining material properties preferably compatible with code rules should be offered to designers.

This paper presents a routine of determining and confirmation of material properties for further finite element analysis of a structural element by means of inverse analysis.

Elementary tests are carried out in a laboratory. Results of the test become inputs to the first run of inverse analysis.

The inputs to inverse analysis are data obtained in laboratory tests:

- Compressive strength measured in a compressive test on cubes
- Tensile splitting strength measured in an indirect tensile test on cubes
- Load – deflection curve measured on prisms in three point bending test

The basic strengths are used in a FE simulation of the bending test of the prism. In several following runs the material parameters were adjusted until an acceptable coincidence of load-deflection diagram from laboratory test and numerical simulation are reached.

Obtained material parameters can be used in a numerical simulation of the structural element.

4 Verification of the methodology

Proposed routine was verified for fibreconcrete with recyclables and synthetic fibres in FE program ATENA.

Load deflection - curves recorded in a laboratory three point bending test of a specimen 100×100×400 mm without notch (**Fig. 2**) and compressive strength and tensile splitting strength measured on cubes 100×100×100 mm were used for inverse analysis.

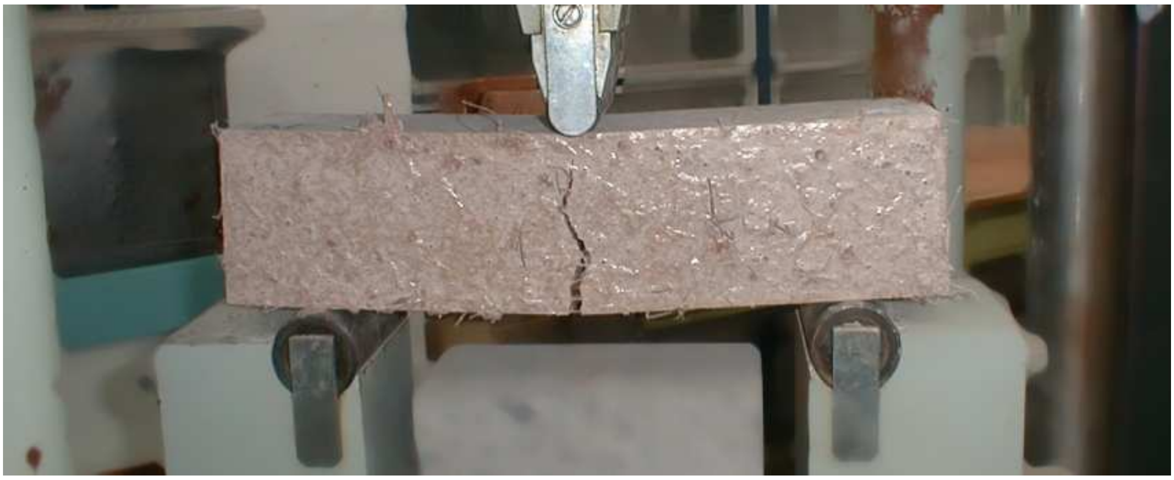

Fig. 2 Three-point bending test of a specimen with synthetic fibres and recyclables

In the behaviour of FRC members the tensile strength and cracking takes the decisive role. Residual strength of FRC must be truly considered to utilize benefits of FRC in the non-linear analysis. ATENA programme offers several possibilities for modelling tensile behaviour.

In material models the governing problem is modelling of crack behaviour. In SBETA material model, which is implemented in ATENA programme, two broadly used approaches are incorporated: model based on a stress-strain relationship and model based on stress – crack opening law.

In a local formulation of the tensile material law following parameters must be determined: c_1 and c_2 are relative values of the tensile stress levels f_1 and f_2 related to the tensile strength f_t, and c_3 is the ultimate strain (**Fig. 3**).

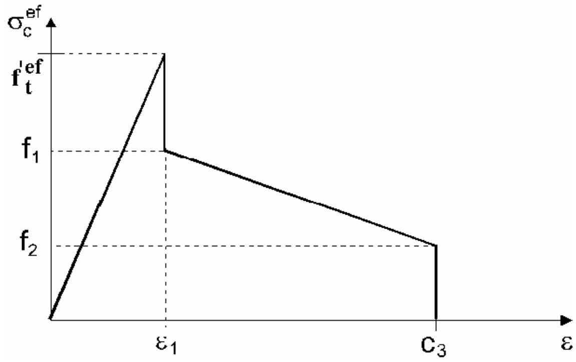

Fig. 3 Steel fibre reinforced concrete model for tensile behaviour based on local strain

In another model an objective material law based on the crack band approach is be used. After cracking, the tensile stress drops to certain fraction of the tensile strength. The ultimate crack width w_c and slope of the linear descending branch are calculated from the fracture energy G_f and the final stress level f_2. Parameters of this model are tensile strength ft, fracture energy G_f, and relative values c_1 and c_2 of the tensile stress levels f_1 and f_2. (**Fig. 4**).

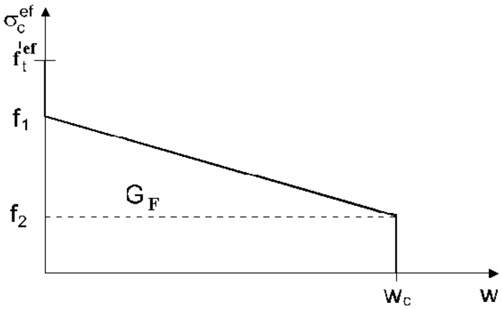

Fig. 4 Steel fibre reinforced concrete model for tensile behaviour based on fracture energy

In both mentioned models non-linear fracture mechanics combined with crack band method and smeared crack concept are exploited. In the smeared crack concept, the real discrete crack is substituted by a band of localized strains. The crack strain is related to the element size, which represents the crack band width L_t. Consequently, the softening law in terms of strains for the smeared model is calculated for each element individually, while the crack-opening law is preserved based on fracture energy consumption To avoid the mesh dependence, which is the problem in stress – strain formulation, the stress on softening part of the stress-strain curve in the first approach (σ-ε) is determined from the crack opening displacement w that is calculated from the inelastic cracking strains ε_{cr} according to the formula: $w = \varepsilon_{cr} L_t$, where L_t is the crack band size that is determined from the element size projected into the direction perpendicular to the crack.

Both material models available in ATENA were used in FE simulation of the laboratory bending test.

Approximations for each material model satisfactory correspond to pattern recorded in a laboratory test. For the first (σ-ε) and second (σ-w) material model formulation the coincidence in the part of the curve, where the first crack forms, is not totally up to the L-D diagram from laboratory test. As we assume for load bearing capacity analysis the crucial influence of residual strength of FRC not the first crack formation, we dare to proclaim the approximation accurate.

The increasing potential of the computer technology enables new ways of structural analysis. The non-linear finite element simulation is a useful tool for analysis of fibre reinforced concrete structures both under service and ultimate loads. FE analysis enables to exploit load-bearing capacity, which is usually neglected or diminished in codes or in linear analysis.

Considering the assessment of reliability, some outstanding structural designs demand to leave traditional analysis based on limit states, where uncertainties of material properties are affected by partial safety factors, and proceed to probabilistic approaches to structural reliability assessment.

Present progress in computer analysis and possibilities of simulation of structural behaviour enable employing of a probabilistic analysis of the structure. In a borderline from the deterministic to the probabilistic determination of material properties material parameters could be sought for by a random study. In a first run of such study deterministic calculation is performed. In a similar way as for the previous method of material parameters evaluating for the first computer run of the analysis the material properties are defined and a deterministic FE analysis is performed. The material input parameters and other input parameters used in a deterministic analysis are used as mean values for random distributions of selected variables. Already a small number of samples could give a reasonable estimation of stochastic parameters of the structural response.

5 Conclusions

The new material has higher tensile strength and ductility and improves behaviour of the structural element in comparison to common concrete. An investigation of behaviour of concrete with aggregate from recycled concrete in a structural element was performed and compared to behaviour of the same element with fibres dispersed in the mixture. The test showed that behaviour of the material reinforced with fibres changed significantly. For application of investigated material in structural members it is necessary to provide adequate methods for design. On the constitutive level the material model has to reproduce the failure modes important for the structural behaviour. Material parameters and material models suitable for the numerical simulation and their effect on the analysis are discussed. Comparison of numerical results with measured values is presented. The aim is to provide more information and a new tool for conventional design using recycled concrete construction and demolition waste material in fibre concrete structures.

Transition from an intention of an FRC with recycled aggregate application to the actual production of an element is very demanding process. Therefore only simple elements were tipped for the first phase of the future production. Operating conditions in a production plant are different from conducting laboratory studies. Harmonized components of concrete mixture had to be adjusted and technological process should be verified for each type of concrete and aggregate.

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