Innovative low cost fibre-reinforced concrete. Part I: Mechanical and durability properties

D. Bjegovic
Faculty of Civil Engineering, University of Zagreb, Kaciceva 26, Zagreb, Croatia
Institut IGH, Janka Rakusina 11, Zagreb, Croatia
A. Baricevic & S. Lakusic
Faculty of Civil Engineering, University of Zagreb, Kaciceva 26, Zagreb, Croatia

ABSTRACT: Over the past decades, significant attention has been focused on waste tyre management, since the presence of waste tyres in the environment can have negative effects on sustainable development. Just like most EU countries, Croatia also recycles large quantities of accumulated tyres, although not all by-products are equally reused. Researchers from Faculty of Civil Engineering University of Zagreb investigate possibilities for reusing rubber and steel fibres obtained during mechanical recycling in the construction of concrete pavements. Research results show that innovative and sustainable concrete mixtures, meeting criteria set in relevant standards, and offering cost savings on pavement construction and rehabilitation projects, can be prepared using the mentioned by-products. In addition to environmental benefits, recycled fibres are highly likely to be used as choice material in the future because of cost considerations (they are ten times less expensive when compared to industrial fibres).

1 INTRODUCTION
Croatia started building its motorways in late 1970s. Today, Croatia has more than 1.2 thousand kilometres of modern motorways connecting all parts of the country. Traditionally, road pavements in Croatia are mostly built as asphalt pavements, while concrete pavements are mostly used for building short segments on toll stations, as they present better abrasion and freezing resistance properties, and higher ductility, when compared to asphalt pavements. These pavements are often built or rehabilitated using fibre reinforced concrete, the price of which considerably boosts the overall costs as the price of steel is continuously increasing.

Toll stations usually have no less than 4 to 6 exits, and 600 to 1000 square meters of concrete are usually needed for their construction. The construction work is conducted in segments each measuring approximately 3.5 x 5 m. A schematic overview of two toll station segments is presented in Figure 1.

1.1 Specification of material
Concrete used for rehabilitation of pavement on toll station lanes has to meet several criteria so that adequate mechanical and durability performance can be achieved. In Croatia, these specifications usually involve:
1. Maximum aggregate size (31.5 mm)
2. Compressive strength (min C35/45)
3. Flexural strength (min 5.0 N/mm²)
4. Water permeability (max 30 mm)
5. Freezing and thawing resistance – scaling (mass loss after 56 cycles lower than 0.5 kg/m²)
6. Abrasion resistance – Bohme method (mass loss lower than 21 cm³/50 cm²)

Figure 1. Schematic overview of two toll station segments
2 INNOVATIVE LOW COST FIBRE REINFORCED CONCRETE

Due to their energy absorption capacity, fibres greatly improve concrete properties, namely the durability, ductility and fatigue performance of concrete. Fibre reinforced concrete reduces brittleness as fibres are capable of transferring stress from damaged to undamaged parts of cross section. This is a huge advantage of such composites when compared to ordinary concrete. Service life of pavement structure is reduced by appearance of cracks on the surface of ordinary concrete exposed to environmental and traffic loads. Capability of fibres to restrain cracks, contributes to a longer service life and reduced maintenance of such pavements.

Neocleous et al. 2011 investigate the use of steel fibres recycled from waste tyres for preparation of wet and dry (roller compacted concrete) steel fibre reinforced concrete for pavements. According to analysis results, recycled steel fibres present viable alternative to the industrially produced steel fibres, if used in higher quantities, or if blended with industrially produced fibres (Achilleos et al. 2011). It has been demonstrated that they act as crack arrestors, resulting in substantial increase in toughness, even when debonding and pulling out (Tlemat et al. 2006). Using 2% of recycled steel fibres by mass, better fatigue performance compared to plain concrete is achieved (Achilleos et al. 2011), while similar structural behaviour of innovative and ordinary fibre reinforced concrete has been confirmed (Pilakoutas et al. 2004; Aiello et al. 2009).

Durability parameters are highly significant for achieving the expected service life of structures. The accelerated corrosion investigation (Graeff et al. 2009) points to good resistance of recycled fibres, as compressive or flexural behaviour of investigated material has not been reduced. Visual inspection shows intensive external corrosion of recycled fibres, but internal inspection reveals just a few signs of corrosion.

If service life of concrete pavements is compared with that of asphalt pavements, it can be seen that the former pavements last twice as long (Achilleos et al. 2011). Presence of fibres, which are usually steel fibres increases the price of concrete per cubic metre. The price of industrially processed steel fibres amounts to approximately 1500 €/t, which can increase the price of concrete for more than 50 percent for every cubic meter, when compared to the price of ordinary concrete. Unfortunately, today the awareness of long-term ownership costs is almost inexistent, although costs can be brought down considerably if quality materials are used. The analysis of earlier studies reveals that extensive research is needed on possible interactions between industrial and recycled fibres.

3 EXPERIMENTAL RESEARCH

Research on possible interaction of by-products from mechanical recycling of waste tyres, so as to enable production of low cost fibre-reinforced concrete, was performed at the Faculty of Civil Engineering University of Zagreb. Extensive research conducted in collaboration with industrial partners included testing of more than one thousand concrete specimens, so as to determine 16 different properties. Only a part of this research, focusing on possible synergy between industrial steel fibres, recycled steel, and textile fibres with rubber granulates, will be presented in this paper.

3.1 Materials and mix proportions

The following constituents were used in the preparation of concrete: CEM II/BM SV 42.5 N, combination of crushed and alluvial aggregate, silica fume, superplasticizer (polycarboxylic ether hyperplasticiser), air entraining admixture, 35 mm long industrial fibres with bent ends and 0.55 mm in diameter, recycled steel and textile fibres obtained during mechanical recycling of waste tyres (irregular shape and dimension), and rubber particles (diameter 0.5 – 2 mm) (Fig. 2).

The mixing procedure was adopted due to addition of rubber particles which were initially treated in a saturated calcium hydroxide solution (Bjegović et al. 2010; Bjegović et al. 2011) to take into account the presence of zinc stearate on rubber surface
causing inadequate bond at the rubber/cement paste interface. The mixture composition is given in Table 1.

Industrial produced steel fibers

By products from mechanical recycling of waste tyres

Steel fibers Textile fibers Rubber

Figure 2. Industrially produced fibres and by-products from mechanical recycling of waste tyres

3.2 Mechanical properties

Specifications for concrete pavements are described in the previous paragraph (cf. 1.1). All results were obtained at the age of 28 days. Adequate mechanical properties of concrete delay formation of cracks due to traffic load, temperature-induced thermal stresses, freeze-thaw damage, water infiltration, ageing effects, and so forth. Concrete pavements have to satisfy criteria set for freezing resistance which is why the use of the air entraining admixture is mandatory. For that reason, all further comparisons were made using 100I0RA as reference mixture.

With the progress of analysis, it became obvious that incorporation of rubber particles (5 percent of the total volume of aggregate) causes minimum reduction if correlation is done with the mixture containing the air entraining admixture only (Fig. 3a). Graeff et al. 2009 indicate that compressive strength is somewhat lower when recycled fibres are used, if comparison is made with ordinary fibre reinforced concrete. This was not confirmed during the analysis presented in this paper (Fig. 3b).

Flexural strength is yet another important criterion for concrete pavements (cf. 1.1). Concrete pavements are rigid pavements which means that, due to their high stiffness, the load is distributed over a wide surface area of the subgrade. The structural capacity is ensured by the concrete slab itself. Accordingly, its flexural capacity is an important property, and it is additionally improved by the presence of fibres. Testing of flexural strength using the three point loading test confirmed positive influence of recycled fibres on flexural strength (Fig. 4). All mixtures met the design criteria, with no difference in mixture composition.

Modulus of elasticity also provides very important information about the material, describing tendency of material to deform elastically when force is applied. The modulus of elasticity of rubber is extremely different from that of the steel: it is very low for rubber and very high for steel, compared to the normally used aggregate. There is also a certain difference between industrially produced and recycled steel fibres, which is due to different production procedures, although the results do not point to any difference between mixtures containing different fibre ratios (Fig. 5). The influence of rubber was recorded, and it was revealed that this material consequently causes decrease of values in rubberized concrete. The reduction of elastic modulus points to higher flexibility, which may be viewed as a positive gain in mixtures used for concrete pavements.
3.3 Durability properties

Durability parameters of a material are of major interest when material is directly exposed to environmental loads, which is obviously true for pavements. It has been established that the presence of de-icing salts during winter is very harmful for the microstructure of concrete. In order to obtain an adequate resistance, the presence of an air entraining admixture in mixture is obligatory. Distresses due to volume changes during freezing are minimized with an additional quantity of closed pores entrapped by admixture. Benazzouk et al. 2006 indicate that rubber particles, due to their rough surface and hydrophobic properties, increase content of air in mixtures, which could be beneficial for durability of materials during the freezing period. In addition, low modulus of elasticity allows rubber to act as a small spring and absorb pressure of water in capillary pores during freezing.

Although it is indicated in specifications for pavements that resistance to freezing should be determined using the weight loss method, this resistance was determined using the dynamic modulus of elasticity method because the weight loss method is not suitable for fibre reinforced concrete (ACI Committee 544 2009). Criteria set in specifications for concrete pavements were further defined through reduction of relative dynamic modulus. The study of correlation between the mass loss in the presence of salts, and relative dynamic modulus (Hranilović Trubic, 2011), shows that the mass loss of 0.5 kg/m² is approximately equal to a ten percent reduction of the relative dynamic modulus after 56 cycles for air entrained concrete. After analysis of results, it can be seen that the presence of by-products from mechanical recycling of waste tyres is compliant with all criteria (cf. 1.1, Fig. 6).

![Figure 6](image-url) Freezing resistance: a) Influence of rubber particles b) Influence of different fibre ratios and by-products

It can furthermore be observed that the material under study meets both water permeability and wear resistance criteria (cf. 1.1), without any difference in the quantity of by-products (Fig. 7). The water permeability slightly increases with an increase in rubber content in mixture. In fact, recycled textile fibres contain an additional quantity of rubber, as they cannot be properly cleaned during the recycling process. This additional quantity causes a slight increase in water permeability when compared to mixtures without textile fibres. This increase has already been explained in literature by low quality bond at the rubber/cement paste interface (Ganjian et al. 2009).

![Figure 7](image-url) a) Influence of by-products on water permeability b) Influence of by-products on wear resistance

3.4 Economic eligibility

After extensive study of mechanical and durability properties of this innovative material, it became obvious that the concrete prepared in the course of the study is compliant with all relevant specifications for concrete pavements. In addition, an economic analysis was performed (Table 2).

<table>
<thead>
<tr>
<th>Mixture</th>
<th>€ / m³</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>100I0RA</td>
<td>€112</td>
<td>0%</td>
</tr>
<tr>
<td>70I30RAGT</td>
<td>€104</td>
<td>7%</td>
</tr>
<tr>
<td>50I50RAGT</td>
<td>€97</td>
<td>14%</td>
</tr>
<tr>
<td>0I100RAGT</td>
<td>€80</td>
<td>33%</td>
</tr>
</tbody>
</table>

If calculations are done per m³, it is clear that savings of up to 33 percent can be made if recycled fibres alone are used. These savings concern only the economic viability of this new low-cost material, although environmental savings are also considerable, which is why this material can rightly be characterized as extremely viable.

4 CONCLUSIONS

The present economic situation is certainly favourable for application of innovative low-cost materials. Croatian investments in construction industry amounted to about 7 percent of the GDP in 2009, out of which most sums were invested in the construction and rehabilitation of motorways. Possible reduction in motorway rehabilitation costs, ranging from 7 to 33 percent, makes this research important not only
for the scientific community but for the society in general.

The analysis conducted in this paper implies that innovate low-cost fibre reinforced concrete meets all criteria set in standards, thus making introduction of this recycled material reasonable and justified. The main disadvantage of the studied material is its higher external corrosion compared to that exhibited by standard materials (100I0RA). However, this disadvantage is limited to negative visual appearance of the material, and no negative impacts on material properties have been noted.

Additional positive influences of recycled materials, namely of rubber and textile fibres, will be presented in Part II of this paper, in which their influence on concrete ductility, post cracking behaviour, and impact resistance, will be investigated.

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