MECHANICAL PROPERTIES OF HIGH STRENGTH CONCRETE WITH RECYCLED STEEL FIBRES FROM WASTE TYRES

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Summary: Durability of concrete is highly defined by its possibility to resists cracking. Low tensile strength and brittleness are often responsible for micro cracking of concrete surface and accordingly its lower resistance to penetrability of aggressive agents. In highly aggressive environments with presence of dynamic loadings mechanical properties together with permeability of concrete are detrimental for its durability. High strength fibre reinforced concrete can be solution in these environments because it allows control of the crack opening and assures structural continuity.

Since use of industrial steel fibres in concrete mixture significantly raises the costs of concrete, nowadays the use of supplement materials is explored. Since 2006, when European Commission prohibited any kind of waste tyres disposal, waste tyres became valuable resource. During mechanical recycling of waste tyres is possible to obtain products which are all reusable in concrete industry: rubber, steel and textile fibres.

In this paper use of recycled steel fibres with and without addition of recycled rubber is explored, all in order to obtain high strength fibre reinforced concrete. Although, steel fibres obtained during mechanical recycling of waste rubber are irregular, with different lengths and diameters previous studies showed that they represent good supplement for industrial fibres. Rubber granulates used during this research have diameter from 0.5 to 2 mm. Seven concrete mixtures was prepared during this research including different ratios of industrial and recycled steel fibres (100I0R; 50I50R; 0I100R) with and without addition of recycled rubber (5% by total volume of aggregate). In order to evaluate the influence of combining industrial and recycled steel fibres, with or without addition of the rubber on mechanical properties of concrete following testing was performed: compressive strength, flexural strength, modulus of elasticity, toughness, abrasion, freezing resistance and shrinkage.

1 INTRODUCTION

1.1 Waste tyre management

Large quantities of waste and its inadequate management are one of the leading contemporary problems. Uncontrolled disposal as well as insufficient recycling has negative effect on ecological system causing inadequate living conditions. Sustainable development oblige us to preserve
environment for generations to come, accordingly reuse of waste materials must have priority in front of the use of natural resource.


1.2 Use of waste tyres by-products in concrete industry

Removed from the environment and recycled, waste tyres can be a valuable raw material with a wide range of applications. Previously conducted research [2], [3] showed that by-products form waste tyre recycling (rubber, steel and textile fibres) can successfully be incorporated into concrete, especially when specific properties are expected. By-products are used in different fields of construction industry; industrial floors, asphalt, parts of the drainage systems, rail elements, parts of residential buildings, insulation, and flooring for playgrounds and sport or as an energy source.

Taking into account, that mechanical recycling of waste tyres is environmentally friendly process, without any further gas emissions, by using obtained by-products significant contribution to natural resource conservation is achieved through reduction of new and existing waste amounts. During mechanical recycling of waste tyres three different by-products are obtained: rubber, steel and textile fibres. Rubber is usually used as replacement of aggregate or even as chemical admixture, depending on dimensions. Incorporation of rubber particles in concrete causes reduction of mechanical properties such as compressive and flexural strength, while improvements are seen in terms of reduced modulus of elasticity, improved post cracking behaviour and durability properties such as permeability, capillary absorption, chloride diffusion, etc. [4-7]. Performed studies also pointed the need for improvement of quality bond on rubber/cement matrix interface [8]. Recycled steel fibres found their application in the construction industry as cost-efficient alternative to industrial fibres, during production of precast concrete elements, shotcrete, industrial floors and other construction elements were improved ductility and post-cracking behaviour are of major interest [9], [10]. Until today recycled textile fibres have not found major application in concrete industry although can successfully replace usually applied polypropylene fibres.

1.3 Economic aspects

Current demand for rebar reinforcement in Europe amounts around 12 million tons per year [9] while its price is constantly rising due to significant demand for steel, especially in China and the current price of steel is around 700 Euros per ton. Fibre reinforced concrete is still struggling on the market and is currently taking a small part of the steel demand; however, the complexity of production dictates its price which is currently around 1.500 Euros per ton. On the other hand, the current price of recycled steel is only 150 Euros per ton.

According to data for 2004 [9], and assuming that market rises proportionately, it is evident that the available amount of recycled steel fibres is more than sufficient to replace the industrial fibres. Presented synergy combines economic viability, favourable properties together with positive impact on the environment, allowing all participants in the construction process to acquire profit.

2 EXPERIMENTAL WORK

Special research interest during the project "Concrete track system – ECOTRACK" was to investigate possible positive synergy between industrial and recycled steel fibres (Figure 1). Main objective was to obtain innovative and sustainable concrete which can satisfy criteria established in standards, at the same time assuring cost reductions. Innovative low cost hybrid fibre reinforced concrete is prepared by using small amount of rubber particles (5% by total volume of the aggregate) and steel fibres (30 kg/m3).
Figure 1 Concrete track system – ECOTRACK

Previously conducted research confirmed that each by-product from waste tyres recycling improves special concrete properties: rubber particles - concrete energy absorption capacity together with durability properties, steel fibres - concrete post-cracking behaviour and textile fibres - properties of fresh concrete. Following, research methodology compromise three phases: determination of pre-treatment solution suitable for industry conditions, adequate amount of recycled steel fibres and finally investigation of possible positive synergy between rubber particles and steel fibres. Due to possible special application of investigated material, main task was to prepare concrete with adequate abrasion resistance, ductility and post-cracking behaviour.

2.1 Preparation of the specimens

Specimens were prepared in precast concrete plant according to the mix proportions given in table below (Table 1). Seven mixtures are investigated obtaining different fibre ratios with or without incorporation of rubber particles. Abbreviations used to designate the mixtures represent the amount of different fibre type and presence of recycled rubber. For example: 50I50RAG is mixture containing 50% industrial and 50% recycled fibre in total fibre content, together with 5% of rubber particles by total volume of the aggregate and air entraining admixture.

Used components incorporate: CEM II/BM SV 42.5 N, combination of crushed and alluvial aggregate, silica fume, superplasticizer (polycarboxylic ether hyperplasticiser) and air entraining admixture. Industrial fibres were 35 mm long with diameter of 0.55 mm and bent ends, while Croatian factory for mechanical recycling of waste tyres supplied needed amounts of recycled steel fibres (irregular shape and dimension) and rubber granulates (diameter 0.5 – 2 mm) (Figure 2a).

Figure 2 a) industrial and recycled steel fibres, b) rubber pre-treatment

Mixing procedure was adopted due to addition of rubber particles which were initially pre-treaded in saturated calcium hydroxide solution [11], [12] due to the presence of zinc stearat on rubber surface [13] causing inadequate bond on the rubber/cement paste interface (Figure 2b).
Table 1 Mixture composition

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Cem.  (kg)</th>
<th>Water (l)</th>
<th>Aggre. (kg)</th>
<th>Superpl. (kg)</th>
<th>Air entrain. (kg)</th>
<th>Silica fume (kg)</th>
<th>Rubber (kg)</th>
<th>Recycled fibres (kg)</th>
<th>Industrial fibres (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100I0R</td>
<td>420</td>
<td>170</td>
<td>1743</td>
<td>2.31</td>
<td>-</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>100I0RA</td>
<td>420</td>
<td>170</td>
<td>1743</td>
<td>2.31</td>
<td>0.25</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
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<td>170</td>
<td>1743</td>
<td>2.31</td>
<td>0.25</td>
<td>21</td>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>0I100RA</td>
<td>420</td>
<td>170</td>
<td>1743</td>
<td>2.31</td>
<td>0.25</td>
<td>21</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>100I0RAG</td>
<td>420</td>
<td>170</td>
<td>1656</td>
<td>2.31</td>
<td>0.25</td>
<td>21</td>
<td>18.90</td>
<td>0</td>
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<tr>
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<td>170</td>
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<td>2.31</td>
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<td>2.31</td>
<td>0.25</td>
<td>21</td>
<td>18.90</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

Irregular shape and dimensions as well as recycling process causes decrease of the recycled steel fibres properties comparing to the industrially processed fibres. It is therefore believed that by combining industrial and recycled steel fibres, hybrid fibre reinforced concrete could be prepared with adequate toughness and ductility. Additional enhancement of concrete properties is provided with presence of rubber particles using their high energy absorption capacity.

Table 2 Mean value of tested properties (on three specimens)

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Density (kg/m³)</th>
<th>Porosity (%)</th>
<th>Compr. strength (MPa)</th>
<th>Mod. of elasticity (MPa)</th>
<th>Abrasion resists. (cm³/50cm²)</th>
<th>Rel. dynamic modulus (%)</th>
</tr>
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<tbody>
<tr>
<td>100I0R</td>
<td>2.4756</td>
<td>2.3</td>
<td>72.45</td>
<td>39216</td>
<td>-</td>
<td>-</td>
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<tr>
<td>100I0RA</td>
<td>2.4419</td>
<td>3.0</td>
<td>66.50</td>
<td>39135</td>
<td>10</td>
<td>100</td>
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<tr>
<td>50I50RA</td>
<td>2.4469</td>
<td>3.8</td>
<td>66.23</td>
<td>38208</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>0I100RA</td>
<td>2.4538</td>
<td>2.8</td>
<td>65.50</td>
<td>38184</td>
<td>9</td>
<td>97.6</td>
</tr>
<tr>
<td>100I0RAG</td>
<td>2.4375</td>
<td>2.6</td>
<td>61.84</td>
<td>35169</td>
<td>8</td>
<td>92.8</td>
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<tr>
<td>50I50RAG</td>
<td>2.4238</td>
<td>3.1</td>
<td>63.29</td>
<td>34857</td>
<td>7</td>
<td>87.4</td>
</tr>
<tr>
<td>0I100RAG</td>
<td>2.4419</td>
<td>2.6</td>
<td>59.49</td>
<td>34280</td>
<td>7</td>
<td>78.1</td>
</tr>
</tbody>
</table>

By analyzing influence of different ratios of recycled steel fibres on concrete compressive strength it is confirmed that incorporation of fibres in mixture does not have negative effect on compressive strength (Figure 3a, Table 2). Special application of investigated concrete requires adequate freezing and thawing resistance. In order to accomplish required resistance, air entraining admixture is incorporated in fresh concrete mixture. By presence of air entrainment, small air bubblers are becoming part of the matrix. This is essential for achieving adequate durability in freezing conditions [14]. Consequently, reduction of strength is present and amounts approximately 8%. Additional decrease was obtained by incorporation of rubber particles (5% on total volume of aggregate), averagely 7%.
Concrete elastic behaviour is determined by density and modulus of elasticity of its principal constituents as well as characteristics of the interfacial transition zone [15]. Aggregate porosity is factor of its stiffness, presenting its ability to restrain the matrix strain. Taking into account that aggregate represents almost 75% of total composite volume, it modulus of elasticity has major influence on composites modulus. Accordingly, replacement of aggregate with rubber particles has certain influence of named property, depending on the amount of incorporated rubber particles. First due to its significantly lower elastic modulus compared to the aggregate and second due to inadequate quality bond on its interface with cement paste. In hardened composite, rubber particles act as springs causing delay in widening cracks and preventing catastrophic failure usually present in ordinary concrete [16]. Despite the fact that steel fibres have significantly higher modulus of elasticity; their incorporation in mixture has no influence on modulus of elasticity due to their minor volume contribution [17]. If correlation is conducted between composite compressive strength and modulus of elasticity it is confirmed that lower modulus means lower stiffness and consequently lower compressive strengths (Figure 3b, Table2).

Evaluation of energy absorption capability and post-cracking behaviour of the composites was conducted using third point loading test on specimens without notch. Maximum peak load was obtained by mixture containing exclusively industrially processed steel fibres without rubber particles and air entraining admixture (100I0R) (Figure 4). That is in accordance with compressive strength values. Further, follows that different fibre ratios do not cause decrease of composite flexural strength. Decrease obtained for mixtures incorporating rubber is equal as one obtained for mixtures with air entraining admixture. Since adequate freezing and thawing resistance can be obtained only with presence of air entraining admixture, all further comparisons are done using 100I0RA as referent mixture.
Obtained behaviour of mixture containing only industrially processed steel fibres and rubber particles (100I0RAG) is especially interesting since it confirms positive synergy between two [18]. If bearing capacity is expressed as area under $P$-$\Delta l$ curve up to the displacement equal to 2 mm, mixture incorporating both industrial and recycled steel fibres together with rubber particles (50I50RAG) can be considered the same as one incorporating only industrial steel fibres and air entraining admixture (100I0RA). Incorporated rubber serves as crack arrestor without affecting steel fibre capability to transfer stress across the crack. Results indicate that with further optimization of the composite, production of ecologically and economically acceptable material as replacement for ordinary fibre reinforced concrete is possible. Presented material could be extremely interesting due to possible decrease of investment costs from 20 up to 50% per m$^3$.

Abrasion resistance presents important characteristic of fibre reinforced concrete. A relevant procedure for concrete track systems sets abrasion resistance as one of the crucial properties. Testing was performed using Bohme method. Abrasion resistance is usually associated with concrete density and compressive strength, what implies that denser concrete with higher strength has better abrasion resistance. Capability of rubber to absorb and further dissipate accumulated energy assures improvement of concrete abrasion resistance (Figure 5a, Table 2) implying that composite compressive strength is not crucial properties to obtain adequate resistance.
Environmental loads can sometimes be conclusive factor for the structural material. Loads like freezing and thawing cause major degradation of concrete microstructure if chemical admixtures are not used. In order to sustain required durability air entraining admixture must be incorporated. According to the literature [19], [20] rubber particles can be used as replacement for chemical admixture, but rubber particles used during this research have inadequate size (0.5-2 mm) to serve for named purpose. Weight loss is not a recommended method for determining the freeze-thaw resistance of fibre reinforced concrete because material that becomes dislodged from the specimen mass remains loosely bonded by the fibres [21]. Freeze thaw resistance was accordingly evaluated using relative dynamic modulus of elasticity.

Results indicated that after 28 cycles of freezing and thawing, presence of recycled steel fibres in mixture is not conclusive factor for concrete durability if air entraining admixture is incorporated (Figure 5b, Table 2). On the other hand, in mixtures incorporating both rubber particles and air entraining admixture decrease of resistance is present with increasing amount of recycled steel fibres. Although, rubber has potential to act as amortisseur and absorb energy produced by ice formation in hardened composite it is possible that due to inadequate quality bond on rubber/cement paste interface, degradation is more pronounced than in mixtures without rubber. Inadequate interface bond allows additional penetration of water into composite and in such way causes further degradation. Simultaneously, “balling” effect of recycled steel fibres induces additional distress in composite microstructure, at the end probably causing reduction of its durability.

Figure 5: Influence of rubber particles on: a) abrasion resistance (material loss), b) freezing and thawing resistance.
Literature [7] indicates that presence of less stiff aggregate such as rubber should cause reduction of internal restraints and thus increase the length change, so presence of rubber particles causes higher free shrinkage and reduced restrained shrinkage. Performed investigation of free shrinkage between mixtures with the same amount of rubber particles and air entraining admixture indicates that presence of recycled fibres in mixture do not cause additional free shrinkage (Figure 6).

4 CONCLUSION

Inadequate knowledge of by-products from mechanical recycling of waste tyres is currently found to be big obstacle for further use of investigated material in concrete industry. Conducted investigation implies that by additional optimization of concrete constituents, high strength fibre reinforced concrete with adequate properties could be prepared at the same time assuring significant cost reductions.

It was found that joint action of industrial and recycled steel fibres together with rubber particles (50I50RAG) provides adequate properties of hybrid fibre reinforced concrete especially compared to the ordinary fibre reinforced concrete incorporating air entraining admixture (100I0RA). Slight decrease of compressive and flexural strength as well as modulus of elasticity is obtained due to presence of rubber particles, while presences of recycled steel fibres do not have influence on named properties. Positive synergy between rubber particles and combined industrial and recycled steel fibres was determined during toughness evaluation where incorporated rubber serves as crack arrestor without affecting steel fibre capability to transfer stress across the crack. Taking into account adequate abrasion and freezing resistance (if air entraining admixture is used), rubberized hybrid fibre reinforced composite can be used in aggressive environments where its utilization for tailored applications could lead to significant environmental and economic benefits. Although promising results are obtained during presented research, further material optimisation is necessary in order to prepare material adequate for everyday use.
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REFERENCES


