THE IMPACT OF POLYMER RAW MATERIALS FROM THE RECYCLING PROCESS ON THE STRENGTH OF CONNECTORS IN NON STRUCTURAL APPLICATIONS

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Abstract
Waste materials have become a serious problem in many branches of industry, including also civil engineering. The amount of waste generated in civil engineering is still growing, and therefore, the application of recycling in the construction industry is highly justified. In the present paper we demonstrate the effects resulting from the application of polymer raw materials from the recycling process. It particularly involves the recycling of raw materials from polypropylene applied in the production of plastic connectors and their impact on the load-bearing efficiency of fixing elements. The research combines also material characteristics and the properties of the investigated connectors. The research tests carried out on the connectors consisted in the assessment of their load-bearing capacity at fixing places in a base made of concrete class C20/25 or from solid ceramic brick.

Keywords: Recycling; Strength.

1. INTRODUCTION

The term “sustainable civil engineering” has been derived from the notion of sustainable development. The literature provides many examples where the term was quoted [12], [7], [11], or in Poland [8], [13]. The significance of that problem was highlighted in December 2007, when the problem of sustainable civil engineering became one of the six leading areas of economy package referred to as LMI – Lead Market Initiative for Europe. Raw materials extracted from the environment are used for the fabrication of materials and building construction components. In the production process, raw materials are transformed into final products. The parameters of these products determine the generally understood quality of a building. As Thornmark writes [16], it is crucial that we pay attention to the selection of the applied materials in order to maximize the potential of recycling, in particular in buildings having low energy consumption. In the work [1], the authors claim that the reduction of construction wastes should be the main priority of the
integrated management policy. They also present a review of wastes’ structure, basing on the available literature data. Other authors, Thormark, Catarina [17] argue that in order to raise the potential offered by recycling in the future, it should be accounted for already at the designing stage. They limited their research studies to the recycling of construction materials and to the analysis of its impact on the environment. Also Gao et al. [6] described the results that indicated that with respect to the majority of construction materials, the consumption of energy needed to process those materials is lower than the fabrication of new ones. As we can read in [10], the annual production of plastics is growing every year. During a decade (2002–2012) the growth was over 40%, from 204 to 288 million tons. Yet it should be noted here [10] that the production and consumption of plastics in the European Union (+NO +CH) has been for years maintained on a stable level of 60 million tons. Out of the total 25 million tons of wastes generated annually (2012), about 25% was subjected to recycling. The significant role of recycling in the present day world has been demonstrated by the European Committee members who are planning to totally eliminate the disposal of plastics on dumping sites by the year 2025, which means subjecting 100% of plastic wastes to recycling.

The above examples taken from literature clearly demonstrate the significance of the subject discussed in the present paper. The application of plastics in construction products is very wide, starting with all types of fixtures and fittings like handles, baseboards, through insulation elements from Styrofoam plates (expanded polystyrene) and finishing with windows. A considerably large group of plastic products is also made up by connectors. Connectors are construction products used for the execution of fastening works and structural or non-structural joints in buildings. Non-structural connectors, which are the subject of the present paper, can be fabricated from plastics, although the first elements of that type (expansion bolts) were made from the natural fibers from jute. Such expansion bolts were invented by John Rawlings in 1910 who patented them in 1911. For all those years the manufacturers have been applying original, primary materials derived from crude oil processing for the fabrication of such connectors. As it was mentioned above, the growing tendencies to employ all possible means to use rather recycled materials in the sector of plastics processing instigated the authors of the present paper to assess the impact of recycling on the properties of plastic connectors fabricated from recycled plastic materials. The authors of the present paper have demonstrated on the basis of thermal insulation plastic connectors and frame connectors that the percentage share of granulate from the recyling process has significant influence on the load-bearing capacity of fixing works realized with such connectors. The results of the authors’ own research studies involving the use of recycled polypropylene materials for the production of connectors were analyzed.

The present work is also attempting to show that the material characteristics of the recycled materials such as Vicat softening temperature VST, tensile stress, elongation at maximum force are interrelated enough to be applied as parameters for the identification of the materials subjected to assessment.

## 2. EXPERIMENTAL PROGRAM

### 2.1. Materials and mix proportions

Two input raw materials were accepted as a basis for the fabrication of production mixtures, and the range of identification studies of the raw materials was defined.

1. Polypropylene recyclate marked in the further part of the work as R, obtained in effect of the processing of production wastes.
2. Original polypropylene of the type EP340K, manufactured by BaselOrlenPolyolefins marked as M.

After that, six mixtures of the above materials were prepared with different proportions in line with the planned research studies. The mixtures consisted of the following proportions of materials (by weight):

- 100% of the material marked in the further part of the work as “R” (polypropylene recyclate),
- 80% of R and 20% of M; 60% of R – 40% of M; 40% of R – 60% of M; 20% of R – 80% of M; 100% of M.

Each of the prepared mixtures in the amount of about 5-6 kg was described as to its composition, and connector samples were fabricated for research studies. The polypropylene recyclate was also subjected to high-temperature gel chromatobraphy in order to define the values of molecular mass. The obtained results are as follows:

- $M_n$ (number average molecular mass) = 64453
- $M_w$ (weight average molecular mass) = 296277
Further studies involved the original polypropylene which was subjected to multiple processing. Using an injection molding machine, we were fabricating the connectors which were then ground in an industrial milling machine, and the obtained ground material was again subjected to injection to fabricate new connectors. Such an operation was carried out four times. It should be emphasized that during the processing no additives facilitating that process were added. The grists obtained in effect of that process were marked respectively as P1, P2, P3, P4.

The samples were prepared according to the requirements of the Standard PN-EN ISO 3167 [9] for mechanical tests of such materials. The fabrication of moulders was carried out on the injection molding machine CS 47/32-1 manufactured by Vihorlat Snina Zavod Michalovce, with the modernized microprocessor-aided control of temperature. Exemplary samples fabricated for the research studies are presented in the Fig. 1.

2.2. Physicochemical properties of the mixtures

In order to analyze the properties of mechanical connectors, physicochemical properties of the mixtures were defined.

As to material identification, the properties of the material specifying the Vicat softening temperature (VST) were determined with the application of tests which consisted in determining a temperature at which a steel needle of a definite section can delve 1 mm into the sample of the dimensions 10 mm × 10 mm and thickness of 4 mm with the temperature rising in a constant manner.

For the needs of the present work, we applied the method B50 using the force of 50 N and the heating rate of 50°C/h. The measurements were carried out on a two-station temperature tester Vicata (Fig. 2). The result of the test is determined as the average temperature from two testing stations, assuming that the difference of temperatures is not higher than 2°C. Otherwise the tests were repeated.

The next parameter of the material subjected to tests involved tensile strength $\sigma$ and relative elongation $\varepsilon$ at tensile strength. The test consists in stretching a sample fabricated in accordance with the Standard PN-EN ISO 3167 [9] at constant speed. We recorded the maximum stresses at the upper stress limit and the elongation at that limit.

2.3. Testing methods of connectors

The tests involved a connector for thermal insulation applications, type K1-10 with a hammered metal expansion pin (Fig. 3a) and a connector FF1, of the “frame” type with the screwed expansion pin (Fig. 3b).

The analysis involved the reference tests in accordance with the European guidelines [2, 3, 4, 5] as well as the studies surpassing that scope. The scope of reference tests according to the European guidelines is based on the experience gathered for many years by
the European approbation units. The scope of additional tests was based on the observations of Ślusarek, Wilk-Słomka [14] and Kozdoni-Orlik [15] claiming that the temperature of the outer layer of the façade might in unfavourable conditions exceed +70°C. Hence, also the plastic connectors for thermal insulation, and in particular the pressure plate of the connector can be subjected to raised temperatures through the outer lining layer of the ETICS system.

The methodology of the tests was as follows:

- Connectors were prepared from appropriate material mixtures,
- Holes were drilled in the concrete base using a hammer drill with a drill piece of the diameter appropriate for the connector and for a particular test,
- The holes were blown through with air,
- The connector was mounted with a hammer; the steel pin was hammered down until it was level with the surface of the pressure plate, or it was screwed down with a proper torque,
- Concrete samples with the mounted connector were subjected to seasoning, over a required period of time in a heat chamber or in a freezer of a preset temperature (-15°C, +21°C, +40°C, +70°C), or in other specified conditions,
- The mounted connector was pulled out after some specified time,
- While pulling the connector out, the curve of displacement force was recorded and the type of damage was noted (the connector protruding from the hole, broken pressure plate, etc.)

The following research studies based on the European Union guidelines were selected:

- Determination of reference load-bearing capacity (NR). The test consisted in pulling out the connector anchored in the base (e.g. concrete C20/25 or solid ceramics) from the hole made with a drill piece of the nominal size (average diameter) in normal conditions, i.e. 21±3°C.
- The tests determining the impact of temperature on the properties of the connector. This kind of test is carried out in several stages, i.e. in the minimum permissible working temperature. We accepted the following temperatures for the tests: +40°C (N+40) and -15°C (N-15) as the most appropriate for the selected connectors, allowing for the fact that they were made from polypropylene.
- Subjecting the connectors to the long-term impact of raised temperature. In effect, the connector is heated up to the temperature above VST for that material and the expansion zone can be deformed due to its softening. Hence, we can assess in this test to what degree the structure of the connector and its performance are susceptible to the influence of such conditions. The seasoning time at the temperature of +70°C (N+70) is 60 days. After that time, the temperature was lowered for 24 hours to the temperature of +40°C and then the connector was pulled out.
- Reproducing the conditions in the concrete in which the connectors were anchored, or the analysis of the load-bearing capacity of connectors after their conditioning over 60 days in the alkaline solution of the pH = 13.2.

The apparatus applied in the tests:

- A screw injection molding machine for the fabrication of samples for testing plastic materials.
- Heat chambers with temperature control and mechanically enforced air circulation.
- A station for pulling out the connectors from the uncracked concrete base of the range of 35 kN and regulated pullout speed.

A station made up from force transducers HBM U2B 10 kN and HBM C6A 200 kN as well as displacement transducers WA-L 100 HBM combined with the measuring amplifier Spider 8 and software Catman (Fig. 4).
3. RESULTS

3.1. Results of material studies

The material tests involved the analysis of the granulate collected from recycling. The analysis of nuclear magnetic resonance NMR (¹H NMR and ¹³C NMR) carried out on the apparatus Varian 400MHz yielded the presence of polypropylene PP and polyethylene of high density PE-HD. Basing on the NMR analysis, we calculated that the granulate consisted of about 75% of polypropylene and about 25% of polyethylene PE-HD. Having analyzed the spectrum, we determined a possible presence of stabilizer in the form of N-ethylbenzylamine derivative. In order to confirm the carried out analysis, an additional analysis of high-temperature gel chromatography was carried out. The chromatographic peak obtained in effect of the analysis is practically monomodal, assigned to PP with a slight elongation at the end of the peak, which bespeaks of the presence of the polymer PE-HD.

We additionally determined the content of ash, used as filler in the production process of goods made of plastic. The results are presented in Table 1.

![Figure 5. The figure on the left presents the softening temperature for various materials, and on the right the softening temperature for the same material M_100% but for successive grinding operations.](image)

The next series of tests involved the determination of softening temperature acc. Vicat expressed in degrees Celsius. The measurements were carried out for two types of samples. The first type involved the proportion changes of M to R, and the second type involved the analyses for the successive grists P. The results of the measurements are presented in Fig. 5. Then the strength characteristics of the studied materials were determined. The graphs presented in Figs. 6 and 7 show the results of the measurements.

3.2. Research results involving the connectors

Research studies involving the thermal insulation connectors and frame connectors on different bases and in different conditions were carried out. The following annotation was accepted in the analysis: NR – reference pullout strength in the concrete base, N+45 – pullout strength at the temperature 45°C in the concrete base, N-15 – pullout strength at the temperature -15°C in the concrete base, NA – pullout strength after the conditioning in alkalines, N+70 – pullout strength after the seasoning at the temperature +70°C in the concrete base, NC – pullout strength from the ceramic base. 10 measurements were carried out for each of the discussed options.

The analysis was carried out for the measurement results and for a so called characteristic value of pullout strength. The characteristic value is selected as a careful estimation of the value which decides about

### Table 1. Content of ash

<table>
<thead>
<tr>
<th>Sample</th>
<th>Content of ash [%]</th>
</tr>
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<tbody>
<tr>
<td>R – recycling</td>
<td>6.96</td>
</tr>
<tr>
<td>M5 (the same supplier, year 2010, comparative)</td>
<td>4.82</td>
</tr>
</tbody>
</table>
the occurrence of a limit state. Careful estimation consists in defining the average value from the limited measurement set at the confidence level of 95%, that is a careful estimation of the bottom value corresponding to the 5% quantile. Using the classical statistical analysis for the estimation of the characteristic value of the pullout strength parameters we applied the formula $X_{\text{char}} = \mu [1 - k_\alpha V_s]$, with the variation coefficient being calculated from the formula $V_s = \frac{\sigma_s}{\mu}$, where $\sigma_s$ is the standard deviation from the measurements and $\mu$ – the average value of these measurements.

In order to calculate the expansion coefficient $k_\alpha$, with the preset confidence level $p_\alpha$ and with the calculated expanded uncertainty $U$, the measurement result should be placed in the uncertainty range $p_\alpha = P\{x \in (x_0 - U, x_0 + U)\}$ around the true value.
After the transformations we obtain the function $p_\alpha = \varphi(k_\alpha)$ which defines the relationship between $k_\alpha$ and $p_\alpha$, and is tabulated. The tables are commonly available. We can find in the tables that for the normal distribution with the 95% confidence level the expansion coefficient has the value $k_\alpha = 1.96$.

The graphs in Figures 8, 9, 10 present the pullout strength for particular materials. The authors intentionally presented the diagrams in the linear form instead of scatter plots. Such a presentation form of figures is clearer and enables better interpretation of results. With scatter plots, function trends are invisible.
4. ANALYSIS AND DISCUSSION OF RESULTS

When we look at the results presented in Table 1, we can see a difference in the content of ash determined in the samples. Since both samples were collected from the same manufacturer of recycling granulate, it may bespeak of the fact that the deliveries of the input material for the production process were not totally uninterrupted, or the filler content was shaped freely.

Analyzing the obtained results (Fig. 5), we can explicitly state that the softening temperature is increasing with the percentage share of the raw material from recycling. Therefore, we can state that the softening temperature is a characteristic feature of a given material and we can use it to identify particular types of material from recycling.

We can also state that the said feature is not uniformly defined for the material collected from different grinding processes. Analyzing the diagram we can formulate a hypothesis stating that there are no substantial changes in the softening temperature of materials collected from successive grinding processes. Such a hypothesis should be verified statistically with many measurements of each material. It was not done in this work.

Similar conclusions can be drawn when analyzing the next two characteristics of the material: maximum tensile stress and elongation at maximum stress.

We can also observe that the change of one characteristic (softening temperature, maximum tensile stress, elongation at maximum stress) entails a similar change of the two remaining characteristics. The said relation is presented with the use of regression in Fig. 11. The correlation coefficient $R = 0.9338$ with the test probability $p = 0.0458 < 0.05$ confirms the above thesis.

The results of the investigation studies presented in figures 8-10 involving the connectors made from prime materials, mixtures of prime material and material from recycling and the prime material subjected to successive injections and grinding were subjected to analysis and statistical inference.

Analyzing the average pullout strength we can observe that the materials from recycling have substantial impact on the said strength. The impact of percentage share is a significant factor determining the performance of the material in various conditions.

Although the impact is different for different base or different conditions, we can see that the material $M_{40\%}+R_{60\%}$ is optimal for the connectors.
applied for thermal insulation due to average pullout strength in each situation.

We can also observe that the characteristic values have the same runs as the average values. But the noticeable deformations of the runs of characteristic values result from the dispersion of results, which in extreme cases surpass 20%.

In order to be able to apply the material $M_{40\%}+R_{60\%}$ in the industry, the highest pullout strength is not enough. Its performance in all analyzed situations must be the same as that of the original material $M_{100\%}$. In order to verify the performance of this material, the analysis of the correlation between the original material and that from the recycling was carried out. The analyses presented in Fig. 12 were carried out for thermal insulation connectors.

The correlation coefficient is 0.99 with the testing probability $p = 0.00005 \ll 0.05$. Hence, we confirm the hypothesis that in all investigated cases the material from recycling $M_{40\%}+R_{60\%}$ behaves in the same way as the original material. Furthermore, it has higher pullout strength.

It should be emphasized that by raising the recycling share in the material $M_{40\%}+R_{60\%}$ we lower not only the pullout strength, but also the behavior of the material starts to deviate from that of the original material. When analyzing the correlation between the material $M_{40\%}+R_{60\%}$ and the original material, we obtain the correlation coefficients of 0.8678 or 0.6772 respectively. Having analyzed the material $M_{80\%}+R_{20\%}$, we can observe that it behaves in the same way as the original material (correlation at the level of 0.998), but it has much lower pullout strength than the material $M_{40\%}+R_{60\%}$.

A similar analysis is presented in Fig. 13 for frame connectors. The results obtained for frame connectors were slightly different, i.e. the material $M_{60\%}+R_{40\%}$ is the optimal analyzed material.

![Figure 12](image-url)

**Figure 12.** Dispersion graph and correlation analysis for thermal insulation connectors. The horizontal axis represents the pullout strength results of the material $M_{100\%}$ for all analyzed cases, i.e.: NR, N+45, N-15, NA, N+70, NC. The vertical axis represents the pullout strength results of the material $M_{40\%}+R_{60\%}$ for the same cases as those on the horizontal axis.

The correlation coefficient is 0.9894 with the testing probability $p = 0.00002 \ll 0.05$. Hence, we confirm the hypothesis that in all analyzed cases, the recycling material $M_{60\%}+R_{40\%}$ behaves in the same way as the original material. Furthermore, it has considerably higher pullout strength.

It should be emphasized that by raising the recycling share in the material $M_{60\%}+R_{40\%}$, we lower not only the pullout strength, but also the behavior of the material starts to deviate from that of the original material. When analyzing the correlation between the material $M_{40\%}+R_{60\%}$, $M_{60\%}+R_{80\%}$ or $M_{0\%}+R$ and the original material we obtain the correlation coefficients of 0.6237, 0.4058, 0.4660, respectively.

For frame connectors, it is more advantageous to have lower admixture of recycling granulate than for thermal insulation connectors.

Analyzing new materials fabricated in effect of grinding the original material, we can see that the softening temperature is decreasing with each grinding, with the number of grinding processes being insignificant. Similarly, the maximum tensile strength is...
decreasing with each grinding, with the number of grinding processes being insignificant.

It is interesting that successive grindings do not generally have any significant impact on the pullout strength. In order to confirm the above hypothesis the same measurement was repeated from 6 to 10 times. The results in the tabular form are presented in Fig. 14 and Fig. 15.

The next step involved testing the hypothesis of equal averages with the application of t-test for dependent samples. The following hypothesis was verified:

\[ H_0: \mu_P^1 = \mu_P^2, \mu_P^1 = \mu_P^3, \mu_P^1 = \mu_P^4 \]
\[ H_1: \mu_P^1 \neq \mu_P^2, \mu_P^1 \neq \mu_P^3, \mu_P^1 \neq \mu_P^4 \]

The verification of the hypotheses confirmed the data presented on box plots.

Having verified the hypotheses for thermal insulation connectors, we can say that with the exception of one case (KT-15), there are no grounds to reject the hypothesis of equal averages. Only in that particular case did the test show that there were no grounds to accept the hypothesis \( H_0 \) for the averages \( P_1P_2 \).

Having verified the hypotheses for frame bolts, we found that only in the case of NR were there no grounds to reject the hypothesis \( H_0 \). In the remaining cases there were no grounds to accept that hypothesis. Unfortunately, such a situation was affected by the dispersion of results obtained for frame connectors.

5. CONCLUSIONS

1. The material containing the granulate from recycling yields better pullout strength parameters. Therefore, it is well founded to apply recycling in the fabrication of thermal insulation connectors and frame connectors.
2. The rise of the share of granulate from recycling resulted in the rise of softening temperature of the material and the rise of maximum tensile strength and elongation at maximum tension.
3. For thermal insulation connectors the optimal results were obtained for the 60% granulate admix-
4. Irrespective of the type of connectors, the application of recycling granulate has a positive effect on the properties of connectors, with the provision that depending on the type of connectors we apply various proportions of the admixture.

5. The recycling process consisting in successive grindings of the original material does not yield positive results. The findings demonstrate that for the thermal insulation connectors there is no difference between the average values for successive grindings, which means that there is no impact of successive grindings on pullout strength. For frame connectors, there are no grounds to accept the hypothesis of equal averages, yet the pullout strength is lower than that for the original material.

6. The main damage form for the thermal insulation connector was represented by pressure plate rupture, which is presented in Fig. 16. Frame connectors would slip out of the hole. In some parts involving the research on thermal insulation connectors, they would also slip out of the hole, in particular in the tests in raised temperatures. Therefore, the results involving frame connectors were burdened with higher uncertainty and a higher coefficient of variation.
7. With respect to raised temperatures for frame connectors, some of the samples were placed closer to the heating element and some a little further, and in spite of the enforced air circulation the connectors placed closer to the heating element could have had higher temperature, which could have translated into measurement uncertainty. Hence such conclusions involving the testing of equal averages hypotheses.

REFERENCES


