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Waste printed circuit boards nonmetallic powder as replacement for sand in cement mortar

Niemetaliczny proszek z odpadowych płytek drukowanych jako zamiennik piasku w zaprawach cementowych

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Abstract. The nonmetallic powder recycled from waste printed circuit boards (PCB) is used in cement mortar as replacement for sand. The results show that the waste PCB nonmetallic powder causes an increase in air content and improves the water-retention property of fresh mortar, decreases the bulk density of hardened mortar. There is a decrease in the compressive and flexural strengths with the addition of waste PCB nonmetallic powder and the decreasing degree depends on the substitution amount of the nonmetallic powder for sand. The tensile bond strength decreases slowly with the increase of the substitution amount from 0% to 35%. The water capillary adsorption of mortar is close to that of control when 10% and 20% sand is replaced. The use of mortar made with recycled waste PCB nonmetallic powder as sand replacement offers promise for applications as medium weight or light weight concrete, while adding value to a post-consumer electric and electronic material that is now generally treated as solid waste.

Keywords: waste printed circuit boards; nonmetallic powder; cement mortar; water-retention property; compressive strength; flexural strength; tensile bond strength; water capillary adsorption.

Streszczenie. W artykule analizowano możliwość wykorzystania niemetalicznego proszku pochodzącego z recyklingu płytek drukowanych PCB (ang. Printed Circuit Boards) jako zamiennika piasku w zaprawach cementowych. Uzyskane wyniki wskazują, że dodatek proszku PCB powoduje wzrost zawartości powietrza, poprawę zdolności do retencji wody świeżej zaprawy oraz zmniejszenie gęstości objętościowej stwardniałej zaprawy. Obserwowany spadek wytrzymałości na ściskanie i zginanie zależy od stopnia substytucji piasku proszkiem PCB. Przyczepność przy rozciąganiu spada stopniowo ze wzrostem substytucji od 0 do 35%. Adsorpcja kapilarna wody zapraw modyfikowanych jest zbliżona do wartości uzyskanej w przypadku próbki kontrolnej, jeśli stopień substytucji proszkiem PCB jest mniejszy niż 20%. Wyniki uzyskane dla zapraw z proszkiem PCB wskazują także na możliwość ich wykorzystania w betonach lekkich. Potwierdzają także, że zużyte elektryczne i elektroniczne płytki drukowane, uważane za produkty odpadowe, mogą być z powodzeniem wykorzystane w technologii materiałów budowlanych.

Słowa kluczowe: odpadowe płytki drukowane, proszek niemetaliczny, zaprawy cementowe, zdolność retencji wody, wytrzymałość na ściskanie, wytrzymałość na zginanie, przyczepność przy rozciąganiu, adsorpcja kapilarna wody.

It is well known that printed circuit boards (PCB) are the essential part of almost all electric and electronic equipment (EEE) [1]. In recent years, the average rate of worldwide PCB manufacture increases by 8.7%, and this figure reaches 10.8% in Southeast Asia and 14.4% in China [2]. At the same time new technological innovation and intense marketing continues to accelerate the replacement rate of EEE leading to a significant increase of waste PCB. The electronic waste in China mainland arrived at about 2.3 million tons, just behind 3.0 million tons in USA in 2010. The worse thing is that only 10% electronic waste enters the recycling system. At present 40% of global PCB are produced in China and the production process usually generates a lot of pieces of electronic waste and 1% to 2% defective products [3]. The reuse of waste PCB is a focused theme in the field of waste recycling and environment protection [4 – 6].

In general, waste PCB contains approximately 30% metals and 70% nonmetals [7]. Metal is the direct driving force of recycling PCB and the technology has been mature. The typical metals in PCB consist of copper (20%), iron (8%), tin (4%), nickel (2%), lead (2%), zinc (1%), silver (0.2%), gold (0.1%), and palladium (0.005%) [8]. The nonmetal portions of PCB consist of thermosetting resins and reinforcing materials and they also can be reused. But nowadays nonmetals recycled from waste PCB are traditionally treated by landfilling or incineration, which have bad influence on the environment [9 – 11].

The reutilization of the nonmetallic materials from waste PCB is an important subject, not only from the viewpoint of waste treatment, but also with respect to the recovery of valuable materials. Many researchers and experts are exploring the effective and environmental way to reuse recycled nonmetals. The nonmetals can be used to manufacture compound plates. Guo et al. [12] studied a kind of nonmetallic plate (NMP) produced by nonmetallic materials of pulverized waste PCB. When nonmetallic materials content was 20% by weight, the NMP with particle size of nonmetallic materials less than 0.07 mm, has excellent mechanical properties, which results in a flexural strength of 68.8 MPa and a Charpy V-notch impact strength of 6.4 kJ/m^2. Mou et al. [13] presented new methods

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that nonmetals were used to make formative models, compound boards or related products. When compared with traditional materials, such as talc and silica powder, PCB nonmetals improve the mechanical features of these products greatly with comparable tensile and shearing strength and 30% larger flexural strength. The nonmetals could also be used as fillers in thermoplastic or thermosetting plastic products. Yokoyama and Iji [14] have investigated using the recovered nonmetals as a filler for viscoelastic materials made of epoxy resin compound by comparing the powder with ordinary fillers, such as talc, calcium carbonate and silica. The strength properties of the mold sample of the compound with the nonmetals were sufficient for use as a construction material, but a little inferior to those of the reference materials with the silica powder as fillers. The feasibility of using recycled PCB as reinforcing fillers in manufacturing unsaturated polyester (UP) composites was studied by Hong and Su [15]. PCB-modified UP resins had higher Tg and were tougher and stronger than the plain UP because of energy dissipation effects from glass fibers and rigid epoxy resins in the PCB. The impact energy of the specimen increased with increasing the loading of PCB fillers.

Cement mortar and concrete is a great consumption of construction material. If the nonmetallic powder recycled from waste PCB can be used in cement mortar and concrete, the environmental problem will be solved effectively. The earlier study shows that the application of waste PCB nonmetallic powder as admixture in cement mortar is feasible and the strengths are acceptable with the waste PCB nonmetallic powder to cement ratio below 15% [16], but the dosage is limited. The partial substitution of waste materials for sand in concrete has been an active area of research in recent years. In order to increase the using amount of the nonmetallic powder, this paper puts emphasis on the application of the nonmetallic powder as substitution for sand in cement mortar, evaluating the physical and mechanical properties of cement mortar made with the waste PCB nonmetallic powder as substitution for sand when the substitution amount is in the range from 0 to 50%.

Experimental Investigations

Materials. The waste PCB nonmetallic powder used in the research consists of about 60% cured thermosetting epoxy resins, 38% glass fiber, and 2% brominated flame retardants and other additives. The particle size of the powder was mainly in the range from 0.16 mm to 0.63 mm. P·II 52.5R Portland cement according to Chinese standard GB 175 and standard sand according to ISO 679 were used in the experiments. The chemical composition of the cement was listed in Table 1. The gradation characteristics of the sand were listed in Table 2.

Table 1. Chemical composition of P•II 52.5R Portland cement
Tabela 1. Skład chemiczny cementu portlandzkiego P•II 52.5R (zbliżony do CEM I 52.5R)

Component	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	ZnO	SrO
Content (%)	0.21	1.14	4.99	20.8	2.22	0.66	65.2	0.22	0.05	3.22	0.10	0.13

Table 2. The gradation characteristics of the sand
Tabela 2. Skład ziarnowy piasku

mm	2	1.6	1.0	0.5	0.16	0.08
Passing (%)	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 1

Specimen preparation and curing method

The mortar specimens were prepared with water to cement ratio by mass of 0.5 and sand to cement ratio by mass of 3. The waste PCB nonmetallic powder was used as substitution for sand with substitution amount by volume of 0, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50%. The dimensions of the mortar specimens were 40 mm × 40 mm × 160 mm.

The investigation was carried out at 20 ± 2°C and the setting period was 24 ± 2 hours. After the setting period, the molds were removed and the specimens were kept in 20 ± 2°C water. Generally the samples were cured for 3 days, 7 days or 28 days.

Test methods

The air content of fresh mortar was measured using an air entrainment meter made according to DIN 18555/-557 and the air content could be read directly.

The bulk density of the mortar was calculated based on the quality and volume of the sample cured for 28 days after its surface was dried by wet towel.

The water-retention rate of fresh mortar was tested according to DIN 18555-7. During test, the fresh mortar with settled volume was put on a filter-film allowing water filter through, fixed on absorbent filter papers. Then the water absorbed by the filter papers (lost water of fresh mortar) was measured after 5 minutes. The water-retention rate was calculated based on that.

The compressive and flexural strengths were determined according to ISO 679.

The tensile bond strength was measured according to DIN 18555-6. Tensile bond strengths between cement mortar and concrete slab were obtained from a Pull Out test machine.

The water capillary adsorption was measured according to DIN 52617. Before test, the mortar specimens were dried at 70°C for 2 days. The four around surfaces were sealed with EP resin before the upside of the specimens was dipped into water. The water capillary adsorption was calculated based on the adsorbed water at different times.

Results and discussion

Water-retention property. Good water-retention property is beneficial to the construction and properties of mortar. Water-retention rate is a quantitative quota to assess the water-retention effect of mortar. The water-retention rate of mortar increases from 91% to 94.8% with the increase of the substitution amount of the nonmetallic powder for sand from 0% to 15%, as shown in Fig. 1. When the more nonmetallic powder substitutes for sand, the water-retention rate is in a slower growth stage compared to that with the substitution amount below 15%. The water-retention rate of mortar grows from 94.8% to 99% when the substitution amount changes from 15% to 50%. The improvement for the water-retention property of the mortar is probably coming from the good water adsorption of the nonmetallic powder.

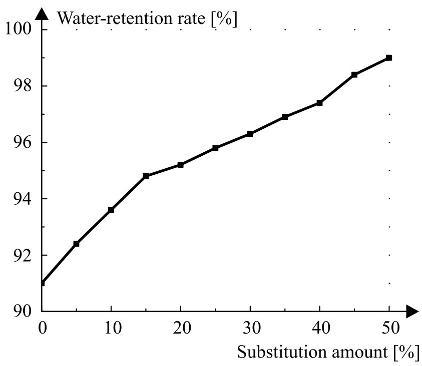

Fig. 1. Relationship between water--retention rate and the waste PCB nonmetallic powder substitution amount for sand in cement mortar
Rys. 1. Zależność między szybkością retencji wody a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

Air content

Air content is important for it has good relation with most mechanical properties of mortar. The air content of the mortar increases from 9% to 13.5% with the substitution amount changing from 0% to 20%, and it achieves 42% when the substitution amount is 50% (Fig. 2). The growth rate of the air content of fresh mortar is slower when the substitution amount is in the range from 0% to 20%, but increases significantly when the substitution amount is higher than 20%. This results show that the nonmetallic powder has air-entrainment effect. It is probably because the finer powder compared with the sand affects the flowability of the mortar, making the mortar not so compact.

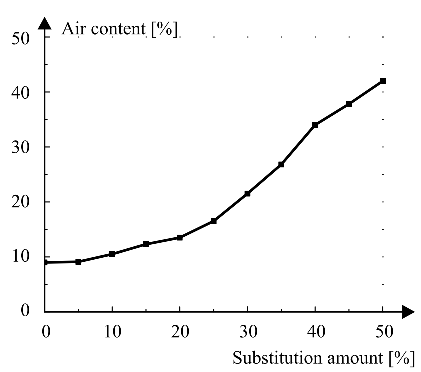

Fig. 2. Relationship between air content and the waste PCB nonmetallic powder substitution amount for sand in cement mortar
Rys. 2. Zależność między zawartością powietrza a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

Bulk density

The bulk density was studied in this paper because it relates to the strength of mortar closely. Fig. 3 shows the relationship between the apparent bulk density and the waste PCB nonmetallic powder substitution amount for sand in cement mortar. The bulk density of mortar declines from 2.28 g·cm^{-3} to 1.92 g·cm^{-3} when the substitution amount changes from 0% to 50%. The decreased bulk density of the mortar made with nonmetallic powder compared with control is resulting from the low density of the nonmetallic powder and the increased air content. The lower bulk density of mortar is good for construction.

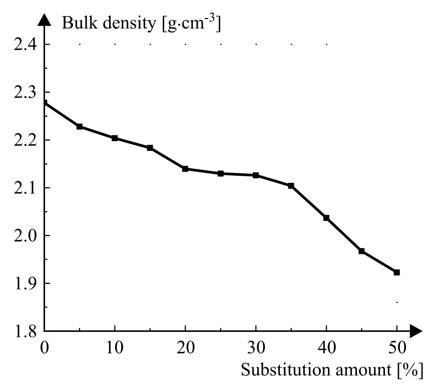

Fig. 3. Relationship between bulk density and the waste PCB nonmetallic powder substitution amount for sand in cement mortar
Rys. 3. Zależność między gęstością objętościową stwardniałej zaprawy a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

Compressive strength

Compressive and flexural strengths are the most significant and basic properties for mortar. The compressive strength of mortar made with waste PCB nonmetallic powder as replacement for sand at curing ages of 3 days, 7 days and 28 days is displayed in Fig. 4. There is a decrease in the compressive strength with the addition of the waste PCB nonmetallic powder and the decreasing degree depends on the powder substitution amount. When the substitution amount increases from 0% to 50%, the compressive strength changes from 23.2 MPa to 10.5 MPa, from 34.9 MPa to 15.7 MPa and from 53.8 MPa to 24.9 MPa for the mortars cured for 3 days, 7 days

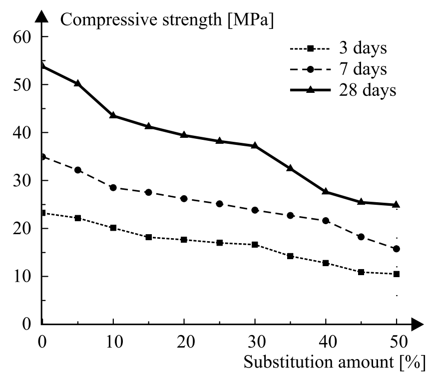

Fig. 4. Relationship between compressive strength and the waste PCB nonmetallic powder substitution amount for sand in cement mortar
Rys. 4. Zależność między wytrzymałością na ściskanie a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

and 28 days, respectively. That is because the not good interaction between the nonmetallic powders and the cement paste. To solve this problem is an ongoing work in our lab.

Flexural strength

The flexural strength of mortar has a similar changing trend with the compressive strength. On the whole, the flexural strength declines with the increase of the powder substitution amount. As the substitution amount increases from 0% to 50%, the flexural strength varies from 4.7 MPa to 2.9 MPa, from 6.4 MPa to 3.8 MPa and from 8.6 MPa to 5.4 MPa for the mortars cured for 3 days, 7 days and 28 days, respectively (Fig. 5). The decline

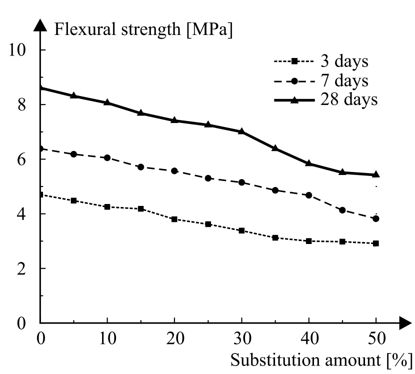

Fig. 5. Relationship between flexural strength and the waste PCB nonmetallic powder substitution amount for sand in cement mortar
Rys. 5. Zależność między wytrzymałością na zginanie a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

of the flexural strength has the same reason with that of the compressive strength.

Tensile bond strength

It is different from concrete that is often used as construction material, mortar is often used as functional material and tensile bond strength is a key factor to affect its application in most occasions. Sot the tensile bond strength was tested in this paper. It can be seen that the tensile bond strength of mortar changes in a small spectrum when the substitution amount is below 35%, as given in Fig. 6. As the substitution amount increases from 35% to 50%, the tensile bond strength decreases at a faster rate, from 0.78 MPa to 0.50 MPa. More than 35% nonmetallic powder replacement affects the tensile bond strength of mortar greatly. The effect of the

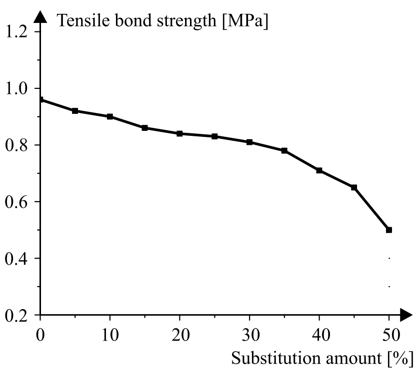

Fig. 6. Relationship between tensile bond strength and the waste PCB nonmetallic powder substitution amount for sand in cement mortar

Rys. 6. Zależność między przyczepnością przy rozciąganiu a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

nonmetallic powder on the tensile bond strength is affected by on one hand the improved water-retention property and on the other hand the bad interface property. The improved water-retention is good for the workability of the mortar and thus the tensile bond strength, but the bad interface structure between the cement paste and the nonmetallic powder has negative effect on the tensile bond strength. In addition when the substitution amount is high the flowability of the mortar become worse and this also affects the mechanical properties of the mortar negatively.

Water capillary adsorption

Water adsorption also influences the application of mortar significantly. The water capillary adsorption of mortar made with the waste PCB nonmetallic powder as replacement for sand within 48 hours is measured and the results are shown in Fig. 7. It can be easily concluded that there is a gain in the water capillary adsorption. The increased water adsorption of the mortar is because that the nonmetallic powder has air-entrainment effect and so increases the porosity of the mortar. However, the water capillary adsorption grows tardily with the increase of the substitution amount from 0% to 20%.

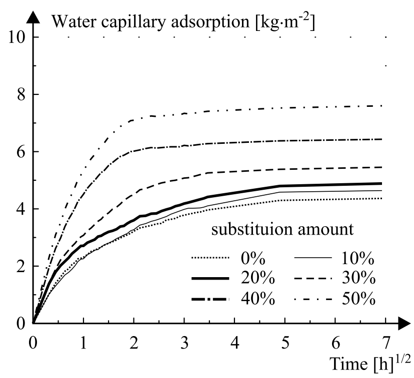

Fig. 7. Relationship between the water capillary adsorption and time of cement mortar made with waste PCB nonmetallic powder as substitution for sand

Rys. 7. Zależność między adsorpcją kapilarną wody a stopniem substytucji piasku niemetalicznym proszkiem PCB w zaprawie cementowej

Conclusions

The waste PCB nonmetallic powder used as replacement for sand in cement mortar improves the water-retention property of mortar evidently. The waste PCB nonmetallic powder has air entrainment effect, making the air content of fresh mortar increase. The bulk density of hardened mortar decreases with the increase of the substitution amount of the nonmetallic powder for sand.

The compressive and flexural strengths drop with the increase of the powder substitution amount. The tensile bond strength of mortar changes in a narrow scope when the substitution amount is below 35%.

The nonmetallic powder replacement for sand results in an increase in the water capillary adsorption, but the increase is not significant when the substitution amount is not higher than 20%.

The use of mortar made with recycled waste PCB nonmetallic powder as sand replacement offers promise for applications as medium weight or light weight concrete, while adding value to a post-consumer electric and electronic material that is now generally treated as solid waste. From this study, the material is acceptable for the constructions that do not need high strengths, for example flower bed, roadblock and some low fences.

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