ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE
OCHRONY ŚRODOWISKA
Rocznik Ochrona Środowiska
Tom 12. Rok 2010 33-45

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Harnessing Waste Fine Aggregate for Sustainable Production of Concrete Precast Elements

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1. Introduction

Cement composites (concrete, mortar, plaster, slurry) are most commonly applied construction materials in the world. Focusing to the environmental pollution problem we are bearing in mind the necessity of a balanced engineering process while applying cement composites. A lot of attention is drawn to the production of cement characterized by large energy consumption (about 4GJ per ton) and a significant carbon dioxide footprint (about 1 tonne of CO_2 emissions per tonne of cement). The worldwide production of cement accounts for almost 7% of total world CO_2 emissions [10]. However, it is very often forgotten that the main component of cement composite is aggregate which covers from 60% to 80% of cement composite volume. Global annual production of concrete, mortar and other cement based composites consumes 20 billion tonne of different aggregate. It means that about 3 tonne of aggregate is used per person per year, which considerably influences natural environment, especially in developing countries.

The production of ordinary concrete usually consumes coarse aggregate (e.g. gravel) and fine aggregate (e.g. sand) in weight proportion approximately equal to 3:1 [13]. If the weight proportion of naturally occurring coarse aggregate and fine aggregate in a specific geographical region were close to 3:1, then the aggregate acquisition for the production of cement composites would be entirely balanced and would be carried out without any aggregate waste. Unfortunately, in majority of cases, natural resources of coarse and fine aggregates can be found in very different weight proportions. For instance in New Zealand there is excess of coarse aggregate and significant deficiency of fine aggregate, while in the Pacific Islands and on the southern coast of the Baltic Sea (East Germany, Poland, Lithuania, Latvia) there is a considerable excess of fine aggregate and deficiency of coarse aggregate [6]. Such natural conditions cause inefficient and unbalanced use of existing resources of mineral aggregate. Coarse aggregate in some cases is obtained from all-in-aggregate by a hydroclassification process which consumes large quantities of water and energy, leaving waste heaps of rinsed sand. From the other hand producers of concrete are often forced to organize a long distance transport of aggregate of specific grading, which is obviously associated with a significant contribution to carbon dioxide emission. Central Pomerania region in northern Poland constitutes a good example of natural disproportion in the occurrence of aggregate with many problems connected with this issue.

Today fine aggregates find more and more applications in the production of diverse kinds of cement composites such as fibre reinforced cement composites, ferrocement and precast elements with dense reinforcement. This issue was widely described and discussed by many researchers e.g. [3, 9, 12]. Sometimes fine sand is utilized as an addition to cement production: CEM IIA-PP 42.5 – up 20%, and CEM IIB-PP 32.5 – up to 35% (Aprobata Techniczna ITB: AT-15-7955/2009).

2. Natural and waste aggregates in Pomerania region

Natural aggregates in Central Pomerania are of glacial origin and they occur in a form of sands and all-in-aggregates. In the region there are 38 documented and described pit deposits [4, 5]. The main mineral component of Central Pomerania aggregate is quartz and crystalline rock, dominated by granite. Figure 1 presents a microscope photograph of Pomeranian sand where white grains are quartz and black grains are granite. The majority of grains have an ellipsoidal shape. The rest of grains have a spherical or flaky shape. As far as smoothness of the grain surface is concerned fine aggregate is composed of angular and partially subrounded grains. In order to generate a statistical model [11, 14] characterizing pit deposits, the whole grain-size distribution was divided into 3 fraction groups: from 0 to 0.5 mm, 0.5 to 2.0 mm and 2.0 to 4.0 mm (fractions reaching over 4.0 mm - 3% by weight of all aggregate, were omitted) which were assigned to the appropriate coordinate axis. Characteristics of all deposits were drawn on the three coordinates system x_1, x_2, x_3 which relate to the percentage share of specific fractions in a grain-size distribution of aggregate. Grading parameters of aggregate deposits in Central Pomerania, in the three coordinates system of fraction groups are shown in Figure 2. The existing raw material base of fine aggregate in Central Pomerania is characterized by a high value of changeability factor V_R understood as a standard deviation quotient of the percentage contents of fractions to a mean percentage contents in the fraction groups. These factors equal respectively: V_R=50% for the fraction group x_1, V_R=37% for the fraction group x_2, V_R=70% for the fraction group x_3.

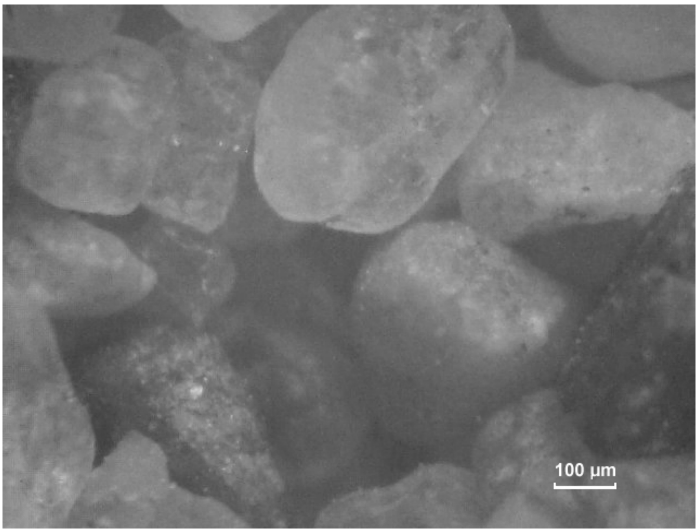

Fig. 1. Microscopic picture of Pomeranian fine aggregate
Rys. 1. Zdjęcie mikroskopowe pomorskiego kruszywa drobnego

Median grain parameter d_m was chosen for the detailed description of aggregate grading. The authors resign from grading description with the use of grading indexes (e.g. Hummle or Abrams indexes), which do not have a significant physical interpretation. Two types of aggregate described by an identical value of grading index may vary significantly as far as water demand is concerned, while composing a concrete mix characterised by the same workability. Therefore it was essential to quantify the fine aggregate grading in a more objective manner.

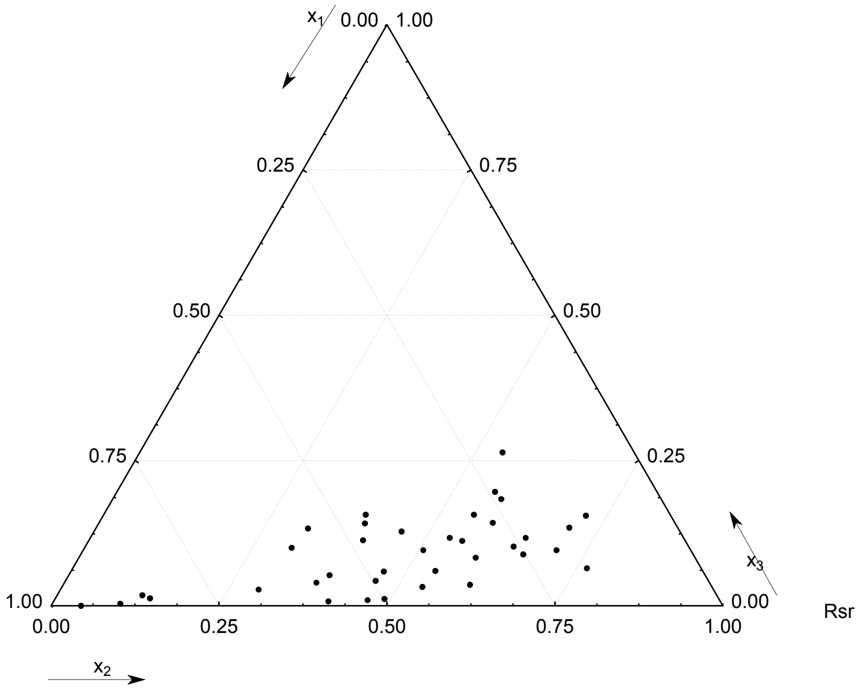

Fig. 2. Grading parameters of 38 aggregate deposits in Central Pomerania
Rys. 2. Uziarnienie 38 złóż kruszyw na Pomorzu Środkowym

Statistical parameter median, is described as the number separating the higher half of a sample (taken from a population), from the lower half, so median grain would be a diameter of hypothetical sieve through which half by weight of the sample passes. Median grain d_m was identified and described with a diameter expressed in millimetres. It divides a sample of aggregate in such a way that half of grains are characterized by higher or equal (to median grain) value of diameter and the other half of grains are characterized by the lower or equal (to median grain) value of diameter. The value of "median grain" is also the central point which minimizes the average of the absolute deviations, as it is in case of the mean. The above fact has a great importance while analyzing fine aggregate grading which is very often contaminated by fine material and gravel particles. Delineated values of d_m for all analyzed pit deposits were presented in a form of a frame chart presented in Figure 3.

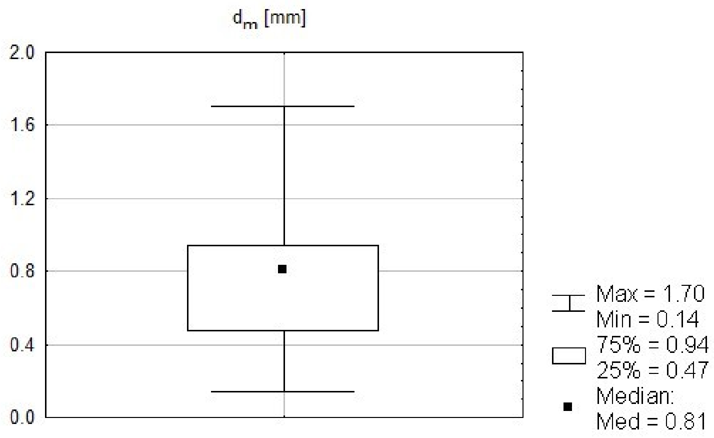

Fig. 3. Frame chart of median grain
Rys. 3. Wykres ramkowy ziarna mediana

In Figure 4 the described aggregates were presented with the help of three different fineness moduli: P_{pp} (fume-sand modulus – the content of fractions up to 0.5 mm), PP (sand modulus - the content of fractions up to 2.0 mm) and P_z (gravel modulus - the content of fractions above 2.0 mm), in relation to median grain diameter. These relations are very important because of the fact, that the moduli P_{pp}, PP and P_z, are used for concrete mix design. Together with the increase of the median grain size value from 0.1 mm to 1.7 mm the amount of fine fractions decrease and the amount of gravel fractions increase. All three relations are very clear and were described by polynomial (cubic) equations (1), (2) and (3).

$$P_{pp} = 130{,}523 - 224{,}175 \cdot d_m + 153{,}161 \cdot d_m^2 - 36{,}291 \cdot d_m^3 \quad (1)$$
$$PP = 108{,}149 - 39{,}929 \cdot d_m + 4{,}156 \cdot d_m^2 + 1{,}407 \cdot d_m^3 \quad (2)$$

$$P_ż = -8{,}149+39{,}929\cdot d_m -4{,}156\cdot d_m^2-1{,}407\cdot d_m^3 \quad (3)$$

where:
d_m – median grain size,
PP – sand modulus,
P_{pp} – fume-sand modulus,
P_z – gravel modulus.

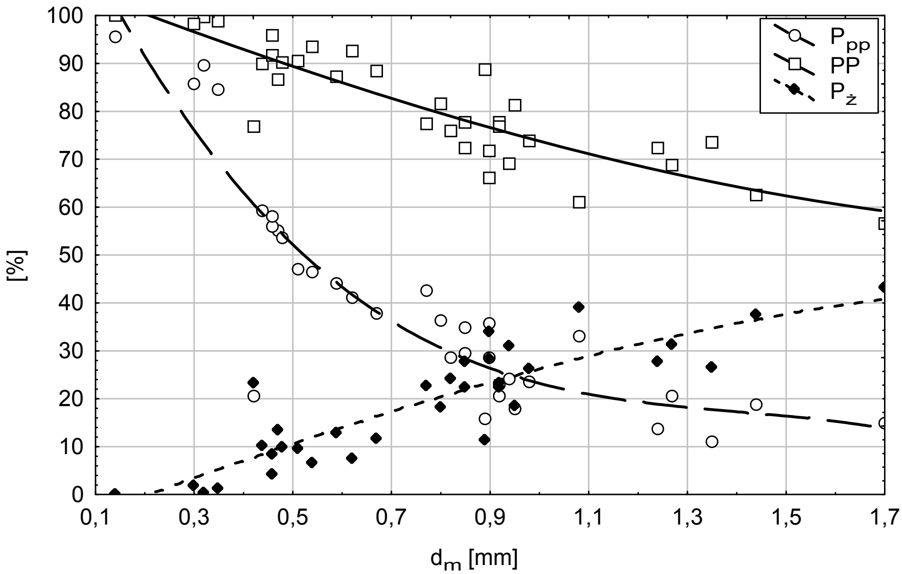

Fig. 4. Fume-sand modulus P_{pp}, sand modulus *PP* and gravel modulus P_z, in relation to median grain

Rys. 4. Punkt pyłowo-piaskowy P_{pp}, punkt piaskowy *PP* i punkt żwirowy P_z, w zależności od ziarna mediana

3. Production of concrete based on waste fine aggregate

Production of ordinary concrete based on locally available fine aggregate is hindered. High transport costs of coarse aggregate from distant pit deposits (often over 200 km) to the precast elements production facility force producers to use the process of hydroclassification of natural all-in-aggregate in order to receive coarse aggregate. Approximately half of documented deposits of aggregate in the Pomerania region is constituted by deposits hydroclassified during the exploitation. During the process of hydroclassification, all-in-aggregate is divided into coarse aggregate and fine aggregate. Waste fine aggregate (WFA) is a by-product of hydroclassification process. Natural all-in-aggregate constitutes from 70% to 90% (by weight) of sand. Because of a huge deficit of coarse aggregate in the region, coarse aggregate obtained during hydroclassification of all-in-aggregate is constantly being sold and always on demand. Fine aggregate received during the hydroclassification process, due to excessive amount of natural sand in the region, is called WFA. This WFA is stored on continuously growing wasteheaps close to the aggregate pits. Figure 5 shows the wasteheaps of WFA near the aggregate pit in Sepolno Wielkie located near the city of Bialy Bor in the Central Pomerania region.

Fig. 5. Wasteheap of hydrograined fine aggregate in Sepolno Wielkie
Rys. 5. Hałda kruszywa drobnego po hydroklasyfikacji w Sępólnie Wielkim

From the technological point of view there are three kinds of aggregate available in the Pomerania region for production of cement composites: natural fine aggregate, WFA and all-in-aggregate. As it is shown in Figure 6, in comparison to natural fine aggregate, WFA is characterized by considerably higher grain-size distribution and a smaller amount of stone dust. WFA is also characterized by higher content of minerals like granite or basalt and crystalline rocks than the natural sand obtained from the same aggregate pit, which is a significant advantage, when taking into account mix designing, mechanical properties and durability of cement composites based on it. Apart from that, WFA has lower factors of grading changeability and a higher content of crystal rocks than all-in-aggregate out of which it was sifted. WFA sifted during the process of hydroclassification is washed and as a result deprived of clay and other fine material. This fact is of great importance because specific surface of aggregate is strongly related to the amount of a very fine particles present in it. WFA is also free from other deleterious substances such as salt contamination, organic impurities and unsound particles, usually present in natural aggregate.

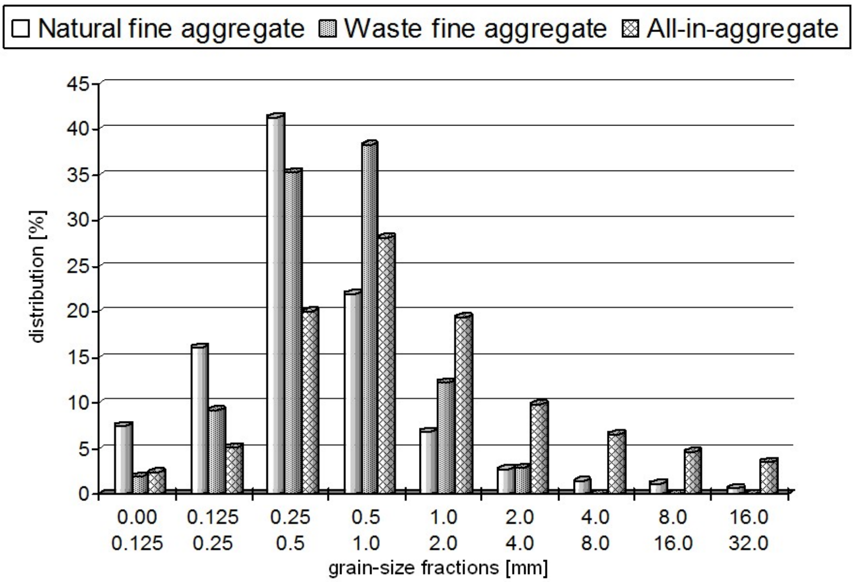

Fig. 6. Grading of aggregates in Central Pomerania
Rys. 6. Uziarnienie kruszyw na Pomorzu Środkowym

In order to stop inefficient use of locally available mineral aggregate and to start recycling WFA for the last 30 years in Central Pomerania there have been conducted several research programmes. These research programmes were concentrated on designing, production technology and mechanical properties (including durability) of cement composites based only on the WFA. These research programmes concerned cement composites produced in the same way as ordinary concrete without any admixtures or additives. It has been established that a cement composite based on WFA is characterized (in comparison to ordinary concrete) by relatively higher shrinkage, cavity, porosity and absorption, law resistance to local mechanical damage, abrasion and acid attack. It is also less frost resistant and characterized by higher water permeability [1, 7].

The grading characteristics of aggregate directly influences parameters of the cement composite based on it. Using fine aggregate as a main aggregate of cement composite affects its behaviour. Large surface area of fine aggregate determines high water demand of all the solids. More water is needed (comparing to ordinary concrete) to maintain the same workability of the fresh concrete mix which was stated by Brzezicki [1] and Hudson [2]. Despite these limitations, for the last 30 years there have been numerous attempts to produce different precast elements (including large scale elements) from cement composites based on WFA. Numerous civil engineering applications of waste fine aggregate cement composites have proved that meticulously made fine aggregate cement composite is characterized by satisfactory strength and durability in order to be applied in civil engineering as a standard construction material [7].

4. Precast elements production

Attempts to produce precast units based on WFA covered a wide range of elements, starting from small size pavement elements, through full size wall units, floor slabs and finishing with sewage pipes. From the technological point of view the most interesting were the attempts to produce prefabricated wall and floor elements destined for erecting blocks of flats (up to eleven floors high). The assortment of precast elements produced on the basis of waste fine aggregate cement composites in Pomerania region in different sites and time is presented in Figure 7. There are presented full size wall elements (ZWO 8pp; ZWO 10 pw; Wk70 W2.0; Wk70 W 7.0; PS IV; PS IVa), floor slabs (Wk70 S6.3.0; II600.150.24), and roof slabs (PDP 600.150; DKZ 300).

To cast the precast elements described above non-modified (no admixtures and no additives added) concrete mixes were used. The contents of used mixes were as follows: cement 32.5 from 370 to 470 kg/m^3, WFA from 1620 to 1790 kg/m^3 and water from 200 to 210 kg/m^3. Although there was no superplasticizer added, mixes were characterized by workability ranging from 17 to 24 seconds (tested according to the Vebe procedure). Density of hardened cement composite was ranging from 2160 to 2296 kg/m^3, and compressive strength was ranging from 19.6 to 30.9 MPa. The waste fine aggregate cement composites were fabricated in concrete plants which on a daily basis produce precast elements based on ordinary concrete (based on both coarse and fine aggregate). All production processes like mixing, handling, casting, compacting, thermal processing and natural curing, of waste fine aggregate cement composites were conducted employing the same machinery and according to the same procedures that were applied while producing ordinary concrete. The fabricated waste fine aggregate cement composites were characterized by mechanical properties comparable with properties of ordinary concrete. However, in some cases it was associated with 10% increase in the use of cement. Due to the difficulties with the thorough distribution of cement in the mix it was essential to prolong the cycle of mixing from 30% to 50% (depending on the workability of the mix) in comparison to the mixing cycle of ordinary concrete. The best results of mixing were obtained when using pan mixers.

During the production of the waste fine aggregate cement composite mix characterized by workability equal to $t_{Vebe} > 7$ [s] (tested according to the Vebe procedure) there were difficulties with unloading the mixer and loading appropriate means of transport. Further on, the existing rocking and shaking during transport on the way to the casting destination causes tight clinging of fresh mix to the walls of transport container, which in turn makes it considerably more difficult and slower to unload. Filling up the moulds with fresh waste fine aggregate cement composite mix is smooth although it takes a little more time than in case of ordinary concrete. The vibration of the mix with the help of standard vibrators, give a satisfactory degree of compaction. It can be observed that standard vibrators are less efficient and the range of their influence on the mix is smaller than in case of ordinary concrete. Finishing of the upper surface of the fresh waste fine aggregate cement composite elements is less labour intensive and is more precise than in case of ordinary concrete. During thermal processing the increase of strength of the described fine aggregate composites is slower than the increase of strength gained during processing of ordinary concrete. Reaching the expected strength needed to start unmoulding, requires prolonging the time of thermal processing in comparison to thermal processing of ordinary concrete.

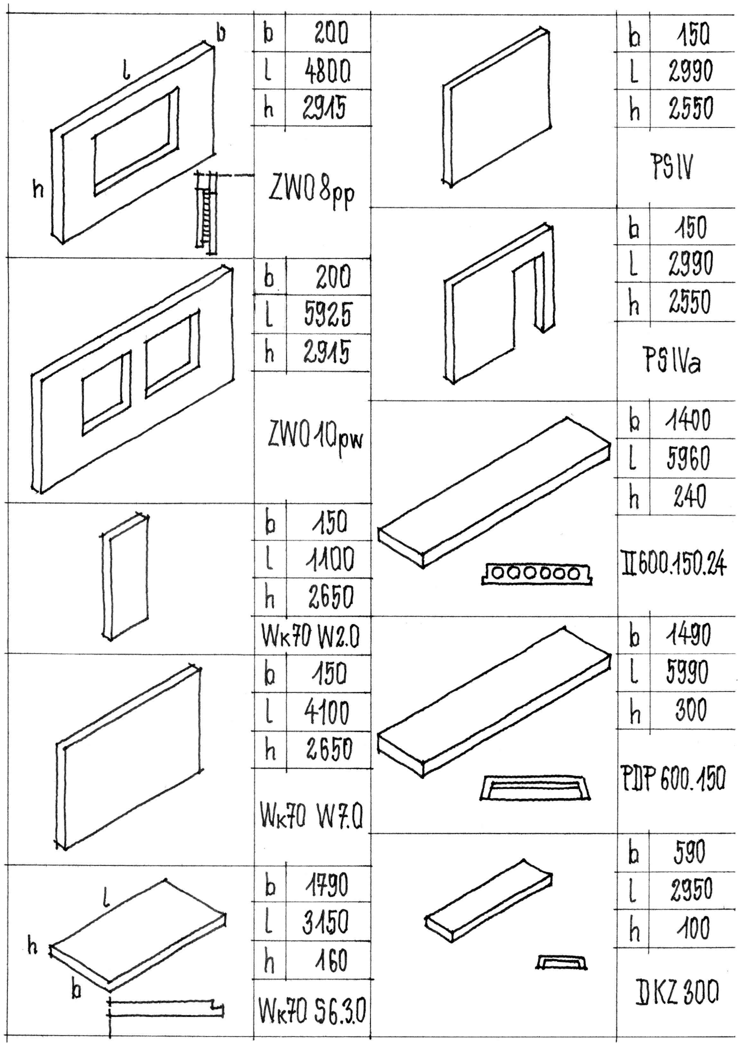

Fig. 7. The assortment of precast elements produced on the basis of WFA in Pomerania region

Rys.7. Asortyment prefabrykatów betonowych produkowanych na Pomorzu na bazie kruszywa drobnoziarnistego kruszywa odpadowego

5. Conclusions

The above experiences gained during the trial production of precast waste fine aggregate cement composite elements. The experiences enable to state that it is possible to produce concrete elements in a balanced way. Taking advantage of local fine aggregate allows for almost no waste production of concrete. Another great benefit of WFA appliance is resigning from costly transport of coarse aggregate not available in the region. Modern additives and admixtures permit the use of WFA in composites on a larger scale than in earlier decades.

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Wykorzystanie drobnoziarnistego kruszywa odpadowego do zrównoważonej produkcji prefabrykatów betonowych

Streszczenie

Niniejszy artykuł dotyczy kompozytów cementowych wykonanych na bazie kruszyw odpadowych uzyskanych w trakcie procesu hydroklasyfikacji pospółki na Pomorzu Środkowym w północnej Polsce.

Na świecie mamy do czynienia z licznymi regionami o małych zasobach naturalnych kruszyw grubych, które są podstawowym surowcem służącym do produkcji betonu zwykłego. W tych regionach zamiast kruszyw grubych występują często duże złoża kruszyw drobnych takich jak piasek i pospółka.

Kruszywa drobne mogą być stosowane do produkcji betonu zwykłego o przeciętnych cechach mechanicznych. Produkcja betonu w oparciu o lokalnie dostępne kruszywa drobne jest tania, co zachęca do produkcji takich betonów, zamiast betonów wykonanych w oparciu o kruszywa grube transportowane z odległych kopalń.