TECHNICAL GUIDELINE FOR THE PRODUCTION AND UTILISATION OF CONCRETE OUT OF RECYCLED AGGREGATES IN HUNGARY



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The Hungarian Group of ***fib*** *developed a Technical Guideline for concretes by using crushed bricks or crushed concrete. Crushed concrete can originate from demolishing or from prefabrication. This paper presents the main parts of the Technical Guideline including classification of crushed recycling aggregates and procedure of preparing the concrete with recycled aggregates.*

Keywords: recycling, concrete, light-weight concrete, concrete element, aggregate, waste, debris, concrete mix design

1. INTRODUCTION

In Hungary, out of construction, demolition and material production a considerable amount of usually not dangerous waste arises, the utilisation of which should be helped if we take into consideration the protection of the environment.

One of the areas of recycling waste arising from construction, demolition and material production is the mixing of concrete, reinforced concrete or possibly stressed reinforced concrete. This is supported by the European concrete and aggregate standards, but they do not deal with the conditions of reusing the waste as aggregate for concrete production. The EN 206-1:2000 standard states that „the aggregates may be natural, artificial or recycled materials from earlier structures". The range of EN 12620:2002 aggregates for concrete, EN 13139:2002 aggregates for mortar, EN 13043:2002 aggregates for asphalt, MSZ EN 13055-1:2002 light-weight aggregates standards is valid for *recycled demolition aggregates*. According to these product standards in case of using such aggregate of which there is not enough experience (like the recycled aggregates), careful testing is to be carried out, and even if having favourable test results may be necessary to prepare unique regulations regarding the range of usability. These aggregate product standards while discussing the harmonisation with the European construction directives, agree in appendix ZA.1 in that all the requirement system for aggregates may be amended with further requirements, for example in the form of national requirements, which are valid together with the European standard.

For the effect of these circumstances did the committee of 20 participants (chairman: *Prof. Tibor Kausay*) of the Hungarian Group of *fib* (International Federation for Structural Concrete) (chairman: *Prof. György L. Balázs*) prepare the "Technical Guideline for concretes by using recycled crushed bricks or crushed concrete", (BV-MI 01:2005 (H)) Concrete and Reinforced Concrete Technical Guideline, which was issued in the August of 2005 (*Fig. 1*).

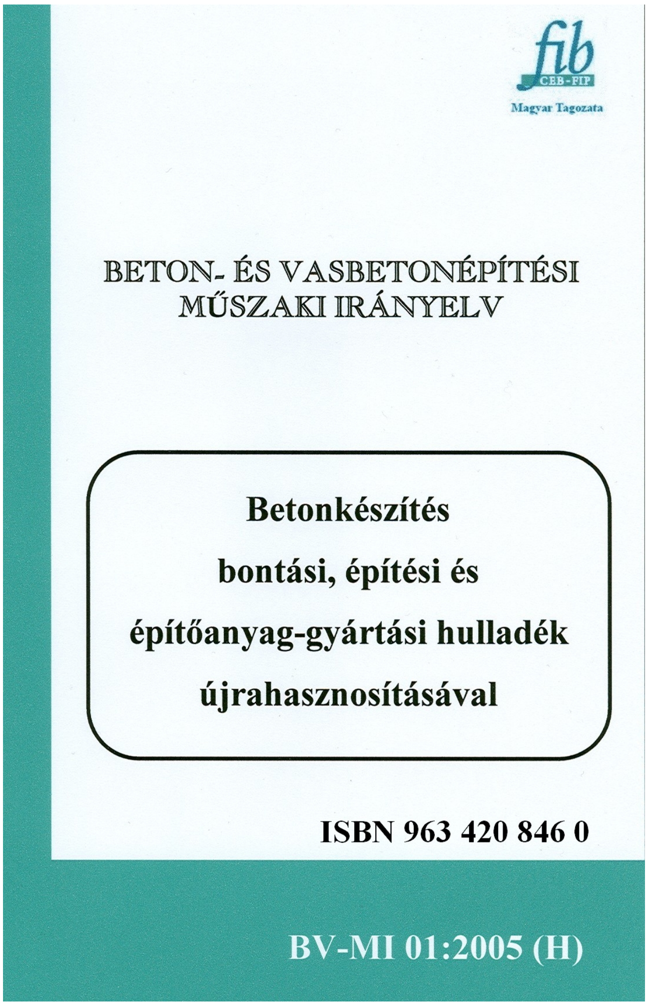


Fig. 1.: Cover page of the Technical Guideline

The Technical guideline was prepared by taking into consideration the six basic requirements given in the appendix of The Construction Products Directive (Council Directive 89/106/EEC) and the connected Interpretative Document issued on the 28th of February 1994 under the number 94/C 62/01.

The Technical guideline deals with: the terms and definitions, the raw materials for concrete mixing, the recycled aggregate concrete, the concrete products out of recycled construction waste aggregate concrete, the concrete products out of recycled construction material production waste aggregate concrete, the reinforced and prestressed concrete products, the technical conditions of the production and utilisation of recycled aggregate premixed concrete – including the requirements and the tests.

In the appendices it discusses the legal and health regulations regarding handling and utilisation of construction waste, the most important technological solutions for processing such waste, the environmental classification of concrete which contains recycled aggregate, gives calculated numerical examples for the evaluation of the compressive strength of concrete, deals with the product certification and the deformation of recycled concrete, gives the bibliographical data of the referred standards, technical guides, literature and laws.

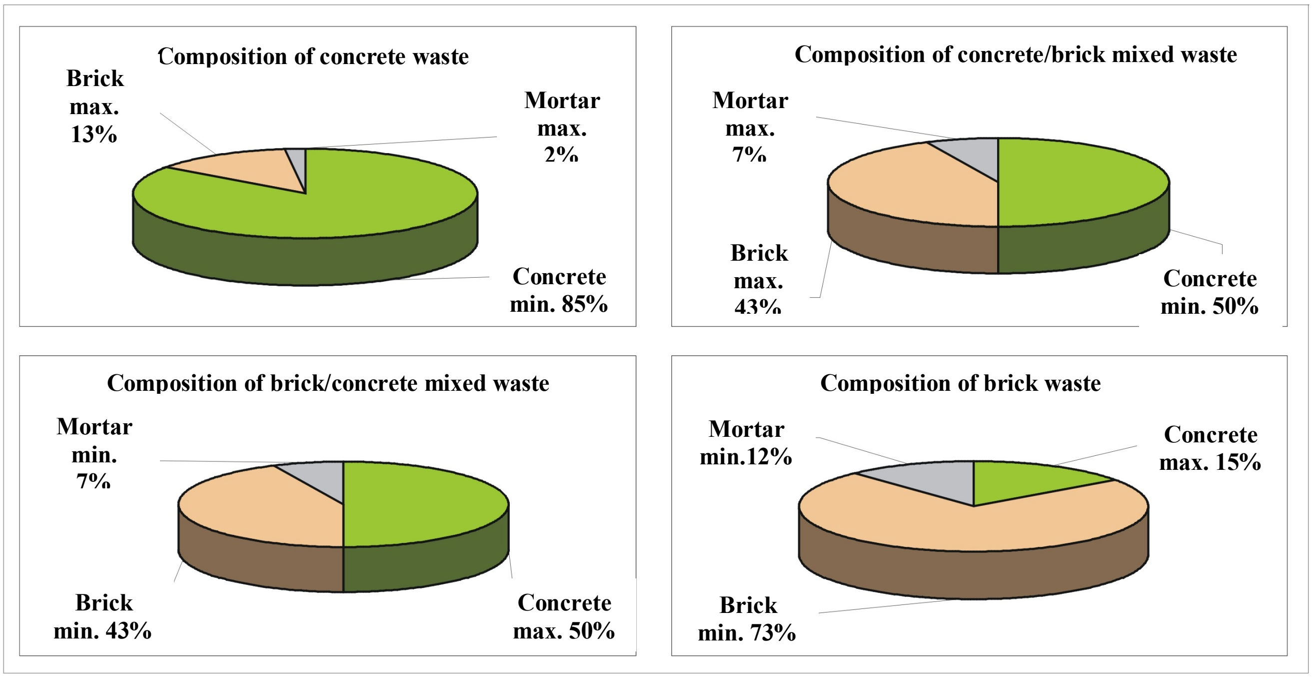
The recycled aggregate concrete is either normal-weight concrete in the C8/10 – C45/55 compressive strength class range, or light-weight concrete in the LC8/9 – LC25/28 compressive strength class range

2. RECYCLED AGGREGATE

The waste arising from demolition, construction and material production must be adequately processed to make it possible for usage as aggregate for concrete (*Fig. 2*). To produce a good quality recycled aggregate the selective demolition is indispensable. The separated by type materials must be crushed in several steps to the appropriate size while cleaned from the undesirables like in case of reinforced and prestressed concrete from the steel and tendons, then fractionalised by size. The fractions are to be stored and transported separately. The fractionalised, recycled aggregate is to be fed into the mixer by fractions after batching. The recycling of the concrete material production waste as an aggregate is usually done in the factory where it is generated. The concrete production waste requires exactly the same crushing, fractionalisation and removal of the fine particles as the construction and demolition waste. From the preparation process only the cleaning may be saved. It is easier to realize the wet fractionalization (washing) of the concrete waste arising from construction material production in the concrete factory then in a mobile processing plant.

Fig. 2: Preparation of demolition waste (*Kiss és Társa Inc.Co.*, Budapest)

The recycled aggregate is to satisfy the requirements of EN 12620:2002 standard regarding normal-weight concrete or EN 13055-1:2002 and the MSZ 4798-1:2004 European and Hungarian standards regarding light-weight concrete about aggregates. By the terms of recycled aggregate the Technical guide understands concrete, mixed concrete/brick or crushed brick. The grouping of so prepared aggregates by constituents may be made on the bases of the constituents of the construction materials in the bigger than 4 mm particle size fraction (*Fig. 3*).



The recycled aggregates and concretes made out of them are classified by their dry densities according to *Table 1*. Based on experiences *concrete waste* may be considered as normal-weight aggregate, the mixed *concrete/brick* waste rarely as normal-weight, generally as light weight aggregate, while the *brick/concrete* and the *brick* waste as light-weight aggregate. This difference is important from the point of the design of recycled aggregate concrete.

Table 1: The classification of recycled aggregates and concretes mixed out of them based on their dry density properties

	Recycled aggregate		Density of concrete at the age of 28 days kg/m^3
	Body density kg/m^3	Bulk density kg/m^3	
Normal-weight aggregate	$2000 < \rho_t < 3000$		
Light-weight aggregate	$\rho_t \leq 2000$	$\rho_h \leq 1200$	
Normal-weight concrete			$2000 < \rho_t \leq 2600$
Light-weight concrete			$800 \leq \rho_t \leq 2000$
Remark: ρ_t notation of body density, ρ_h notation of bulk density in Hungary			

For the recycling of the demolition and construction waste as an aggregate, the following properties are to be determined: *the composition by material type and filth content* by visual examination, *body density* (EN 1097-6:2000), *bulk density* (EN 1097-3:1998), *water absorption* (EN 1097-6:2000), *apparent porosity*, *particle size and grading* (EN 933-1:1997), *fineness modulus* (MSZ 4798-1:2004), *the percentage by volume of the particles under 0.02 mm* by sedimentation (MSZ 18288-2:1984), the water soluble sulphate and chloride content of he surface (MSZ 18288-4:1984), *particle shape* by a Vernier calliper (EN 933-4:1999) or a flow funnel (EN 933-6:2001), *frost resistance* (in case of normal-weight aggregate: EN 1367-1:2007, light-weight aggregate EN 13055-1:2002 standard appendix C), and if necessary in case of normal-weight aggregate *de-icing-salt resistance* (EN 1367-1:2007 standard, appendix B).

Since the origin of the *construction material production waste* is known, – if an aggregate contains only maximum 10% recycled aggregate – may be enough to determine only the filth content, the body density, the particle size, the modulus of fineness and the particle shape. The other properties are defined by the properties of the source concrete, reinforced or presteressed concrete.

Before utilisation must be determined the instant standard water absorption capability of the recycled aggregate according to EN 1097-6:2000.

2.1 Physical properties

Chapter 5. of MSZ EN 12620:2003 puts the regulation of usage conditions of aggregates – according to physical properties – to national competence.

Based on the body density the normal-weight recycled *concrete* or *mixed concrete/brick* aggregates, originating from *demolition* or *construction*, depending on the results of Los Angeles, micro-Deval and magnesium-sulphate tests should be classified by their *physical properties* as given in *Table 2* according to MSZ 4798-1:2004 into *physical groups*. The system of the physical groups acts based on the system of EN 12620:2002 standard. The recycled aggregate may be classified into any of the physical groups if the tests were carried out on the same sized test portion, originating from the same laboratory sample and the material satisfies all the requirements of the physical group in the same time.

The European standards require to carry out these „reference-tests" which are necessary for the classification on samples of particle size 10-14 mm. According to MSZ 4798-1:2004 Hungarian standard the properties of recycled aggregate are to be determined on the so called „alternative-sample" which is a graded aggregate fraction, more precisely on the test sample from it.

If during the acceptance of the frost resistance of the recycled aggregate we are not satisfied with the results of the magnesium sulphate test according to EN 1367-2:1999, then during the direct frost resistance tests according to EN 12620:2002 the climatic conditions of Hungary are to be considered as continental. That is, if the environmental class designation of the concrete out of recycled aggregate is XF1, then the frost resistance class of the aggregate should be at least F_2 or MS_{25}, and if it is XF2, XF3 or XF4, then the frost resistance class of the aggregate should be at least F_1 or MS_{18}.

Table 2: Physical classification of recycled concrete waste and mixed concrete/brick waste aggregates

Property and test method	Testable aggregate size range[a] mm	Physical groups in case of *alternative-tests*						
		Fr-0	*Fr-A*	*Fr-B*	*Fr-C*		*Fr-D*	
					Fr-C1	*Fr-C2*	*Fr-D1*	*Fr-D2*
Los Angeles fragmentation, mass %	3-80	$a_{LA15} \leq 15$	$15 < a_{LA20} \leq 20$	$20 < a_{LA25} \leq 25$	$25 < a_{LA30} \leq 30$	$30 < a_{LA35} \leq 35$	$35 < a_{LA40} \leq 40$	$40 < a_{LA45} \leq 45$
Micro-Deval fragmentation, wet process, mass %	3-20	$a_{MD10} \leq 10$	$10 < a_{MD15} \leq 15$	$15 < a_{MD20} \leq 20$	$20 < a_{MD25} \leq 25$	$20 < a_{MD25} \leq 25$	$25 < a_{MD30} \leq 30$	$25 < a_{MD30} \leq 30$
Crystallisation fragmentation in $MgSO_4$ solution, mass %	2-80	$a_{Mg5} \leq 5$	$5 < a_{Mg10} \leq 10$	$10 < a_{Mg15} \leq 15$	$15 < a_{Mg18} \leq 18$	$18 < a_{Mg21} \leq 21$	$21 < a_{Mg25} \leq 25$	$25 < a_{Mg30} \leq 30$
The highest compressive strength class of concrete[b]		C35/45	C30/37	C25/30	C20/25	C16/20	C12/15	C8/10
[a] The testable aggregate size range, which covers the size of the samples. [b] Based on the body density mainly the fractions above 4 mm of the normal-weight recycled aggregate. The fractions below 4 mm partly or totally are of natural sand (and possibly added fine additives).								
Remark: *Fr* indicates the physical class for aggregates according to the Hungarian notations								

The demolition and construction concrete waste and demolition and construction mixed concrete/brick waste proportion in the total aggregate in the function of the physical group and the compressive strength class of the concrete is according to *Table 3*.

Table 3: The allowed portion of demolition and construction concrete waste and possibly mixed concrete/brick waste in the total amount of aggregate

Compressive strength class of normal-weight concrete, wet curing, according to EN 206-1 $f_{ck,cyl}$ / $f_{ck,cube}$	The allowed portion of demolition and construction concrete and mixed concrete/brick waste in mass percentage in the total amount of aggregate						
	The considerable physical group of the demolition and construction concrete and mixed concrete/brick waste aggregate						
	Fr-0	*Fr-A*	*Fr-B*	*Fr-C1*	*Fr-C2*	*Fr-D1*	*Fr-D2*
C8/10	100	100	100	100	100	100	100
C12/15	100	100	100	100	100	100	70
C16/20	100	100	100	100	100	70	30
C20/25	100	100	100	100	70	30	×
C25/30	100	100	100	70	30	×	×
C30/37	100	100	70	30	×	×	×
C35/45	100	70	30	×	×	×	×
C40/50	70	30	×	×	×	×	×
C45/55	30	×	×	×	×	×	×
C50/60	×	×	×	×	×	×	×
Notation: × Usage of demolition and construction material production waste is not advised							

In the aggregate mixture is only allowed to use recycled material in a bigger portion then the values given in Table 3 if it is proved by laboratory tests that the compressive strength class of the concrete satisfies the prescribed one.

If the quality of the recycled waste from demolition – even if processed carefully – does not satisfy the Technical guide or the concerning European aggregate standard or according to MSZ 4798-1:2004 Hungarian standard is not appropriate for using for normal or light-weight concrete, then it may be improved by the addition of natural aggregate by taking into consideration the data given in Table 3. In this case the conformance of the improved aggregate is to be proved by the compliance of the concrete, reinforced concrete and prestressed concrete properties including conformance to durability requirements.

The origin of the material production waste is known. By careful processing its quality is reliable. In this case the physical, mechanical and chemical analysis and physical classification is only necessary if the recycled aggregate would be mixed to the natural aggregate in more then 10 mass percent, or the necessity of the tests would be generated by other aspects.

2.2 Geometrical properties

The *particle size* of all recycled aggregate or fraction is to satisfy the geometrical requirements of MSZ 4798-1:2004 and EN 12620:2002 standards. The mixtures of the fractions are to follow the boundary curves (*Fig. 4.*). If the recycled aggregate is a mixture of fractions having different body densities, then the values given in mass percentages are to be understood as volumetric ones.

The grading curve of the aggregate may also be *stepped*. According to MSZ 4798-1:2004 Hungarian standard the quantity of the smaller particles, then the missing particle fractions should be present in 30-40 mass percent. The starting point of the step in case of 8 mm max. size is to be at 0.5 mm sieve, in case of 12 or 16 mm max. size at the 1 mm sieve, in case of

20- 24- and 32 mm max. size at the 2 mm sieve, while in case of 48 and 63 mm max. size at the 4 mm sieve. The end point of the step is to be at the closest standard sieve size to 0.4 *D* mm.

The grading curves may shift towards the region of the step in case of bigger fine particle portion demand. An example can be seen on *Fig. 4* (broken line).

The particle *shape index* of sizes bigger then 4 mm is to be in the C8/10 – C16/20 normal-weight and in the LC8/9 – LC16/18 light-weight concrete compressive strength class is at most SI_{40} class, in the C20/25 and LC20/22 or higher classes is at least SI_{20}.

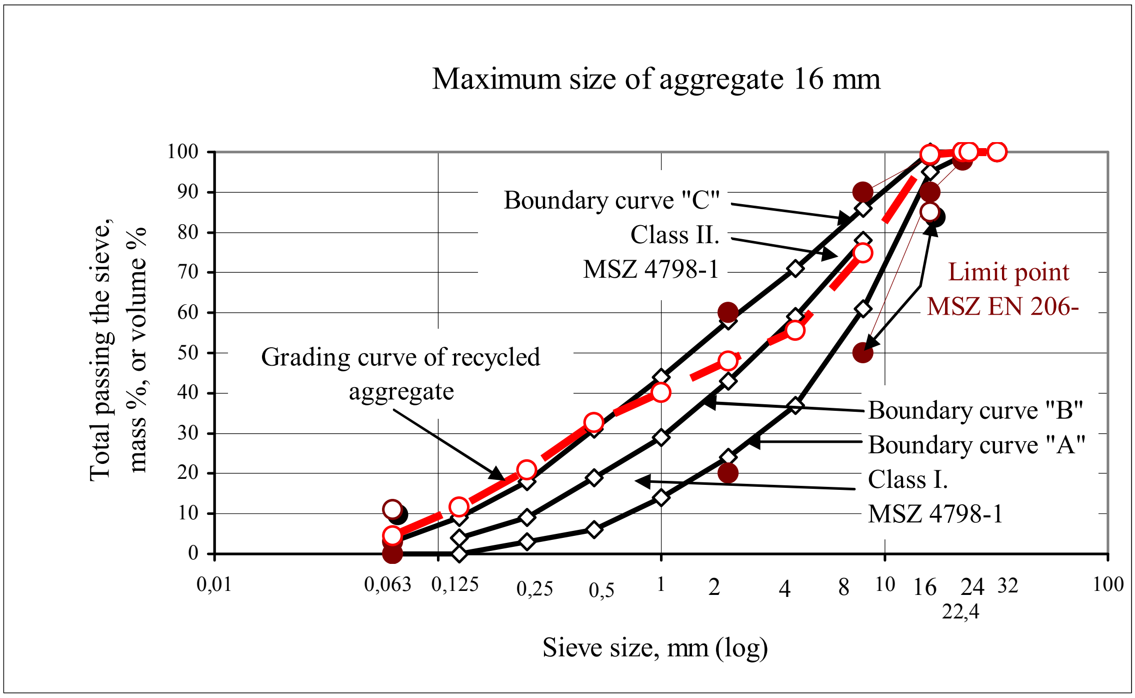


Fig. 4: An example for the grading of recycled aggregate mixture in Hungary

3. DESIGN OF RECYCLED AGGREGATE CONCRETE

The requirement against concrete mixtures made by utilising recycled aggregates is that the concrete, reinforced concrete or prestressed concrete prefabricated product or in situ concrete produced on site is to be durable. The concrete, reinforced concrete and prestessed concrete product or structure is durable, if it is able to resist the loads, stresses and environmental effects under normal service conditions and maintenance for at least 50 years of service life time safely.

The empirical compressive strength average value (cubes) of the concrete samples ($f_{cm,cube,test}$) is to be higher then the az $f_{cm,cube}$ requirement value.

$$f_{cm,cube,test} \geq f_{cm,cube}$$

In Hungary mixed curing is allowed (for the first seven days under 100 % relative humidity followed by laboratory ambient conditions). In this chase the form of th requirement is:

$$f_{cm,cube,test,H} \geq f_{cm,cube,H}$$

Accordingly, in *Table 4* we take into consideration the difference caused by the two different type of curing by assuming that the compressive strength of test cubes cured in 100% relative humidity for 28 days (under water), are of 0.92 % of that of mixed cured (MSZ 4798-1:2004).

Table 4: Required average compressive strength of cubes with 150 mm edges

Compressive strength class of concrete $f_{\mathrm{ck,cyl}}$ / $f_{ck,cube}$	Value of required *average* compressive strength of cubes with 150 mm edge length N/mm^2	
	100% relative humidity curing (wet curing) $f_{cm,cube}$	Mixed curing $f_{cm,cube,H}$
Normal-weight concrete		
C8/10	14	15
C12/15	19	21
C16/20	25	27
C20/25	31	34
C25/30	37	40
C30/37	45	49
C35/45	55	60
C40/50	62	67
C45/55	69	75
Light-weight concrete		
LC8/9	13	14
LC12/13	17	19
LC16/18	22	24
LC20/22	27	29
LC25/28	33	35

The concrete design method can be chosen freely, but the result is to be tested by laboratory tests.

Since the crushed and graded aggregates originating from demolition of structures – mainly of concrete waste – due to the variance of self strength, particle geometry, surface roughness, water absorption capability, resembles much more a crushed stone aggregate than a sandy gravel aggregate. Due to this reason the composition of concretes out of recycled aggregate is more appropriate to be determined by the design methods developed for crushed stone aggregates and the composition of mixed brick/concrete and brick waste aggregate concretes by the design method developed for light-weight aggregate concretes.

From technological point of view it is to be considered that the recycled mixed aggregate, especially due to the big porosity of brick waste has a big water absorption capacity. If we do not care of this excess water demand, it will lead to the change in consistence of the designed concrete. Due to this reason the mixing water demand (m_v) is to be calculated as the „basic water demand" ($m_{v,0}$) plus the „excess water demand" ($m_{v,\Delta}$).

$$m_v = m_{v,0} + m_{v,\Delta}$$

The „basic water demand" is a figure derived from the water/cement ratio multiplied by the cement content. The „excess water demand" may be derived from the short term water absorption capability of the aggregate (e.g. 10 minutes or if necessary by taking into consideration the workability by 1 hour).

Due to the excess mixing water dosage may increase the otherwise necessary mixing time, but it is possible to use wet premixing and the pre-soaking of the light weight aggregate. Due to the strength requirements must be known the total water dosage.

3.1 Design of normal-weight concrete using recycled aggregate out of concrete waste

If the aggregate is such a demolition or construction *concrete waste*, which does not fit in the physical group of *Fr-A*, then the concrete is to be designed according to its physical group to a higher compressive strength class then would be the average compressive strength requirement.

The design compressive strength value of recycled aggregate concrete is obtained by multiplying the average compressive strength – belonging to the compressive strength class of concrete – (*Table 4*) by a multiplicator ζ which is a function of the considered physical group of the concrete waste and the compressive strength class (*Table 5*);

in case of wet curing:

$$f_{cm,cube,recycledconcrete} = \zeta \cdot f_{cm,cube}$$

in case of mixed curing:

$$f_{cm,cube,H,\ recycledconcrete} = \zeta \cdot f_{cm,cube,H}$$

We have derived the function of ζ multiplicator in the function of $f_{ck,cube}$ characteristic value for the chase of *Kf-D2* physical group:

$$\zeta_{D2} = 1{,}7343 - 0{,}1477 \cdot \ln(f_{ck,cube})$$

Since the regression function of the ζ multiplicator with an acceptable approximation follows the quotients of the subsequent characteristic compressive strength class values (e.g. 45/37=1,22; 37/30=1,23; 30/25=1,20; 25/20=1,25; 20/15=1,33), so in case of the recycled aggregate in physical group *Fr-D2* we design for a one higher compressive strength class than would be necessary.

The values of the ζ multiplicator belonging to the other physical groups may be obtained by linear interpolation between the ζ values of the *Fr-A* and the *Fr-D2* groups (*Table 5*).

Table 5: Compressive strength multiplicator (ζ) taking into consideration the physical group

Compressive strength class of concrete according to EN 206-1 standard $f_{ck,cyl}$ / $f_{ck,cube}$	ζ_{D2} = 1,7343 – 0,1477·ln($f_{ck,cube}$)	The ζ **multiplicator,** used for the calculation of the target mean strength of concrete at the age of 28 days, which is proportionated by the concrete waste portion, in the function of the related physical group of the concrete waste, according to *Table 3.*						
		Fr-0	*Fr-A*	*Fr-B*	*Fr-C1*	*Fr-C2*	*Fr-D1*	*Fr-D2*
C8/10	1.39	1.00	1.00	1.13	1.19	1.26	1.32	1.39
C12/15	1.33	1.00	1.00	1.11	1.17	1.22	1.28	1+ 0.7·0.33 = 1.23
C16/20	1.29	1.00	1.00	1.10	1.15	1.19	1+ 0.7·0.24 = 1.17	1+ 0.3·0.29 = 1.09
C20/25	1.26	1.00	1.00	1.09	1.13	1+ 0.7·0.17 = 1.12	1+ 0.3·0.22 = 1.07	×
C25/30	1.23	1.00	1.00	1.08	1+ 0.7·0.12 = 1.08	1+ 0.3·0.15 = 1.05	×	×
C30/37	1.20	1.00	1.00	1+ 0.7·0.07 = 1.05	1+ 0.3·0.10 = 1.03	×	×	×
C35/45	1.17	1.00	1.00	1+ 0.3·0.06 = 1.02	×	×	×	×
C40/50	1.16	1.00	1.00	×	×	×	×	×
C45/55	1.14	1.00	×	×	×	×	×	×
C50/60	-	×	×	×	×	×	×	×
Legend:		× Usage of waste from demolition, construction or material production is not recommended.						

In Table 5 increment above 1.00 of the values of the ζ multiplicator was proportionated by the portion of the concrete waste in the aggregate according to *Table 3*. For example the concrete waste in *Fr-C2* physical group may only be of 70 mass percent of the aggregate used for concrete of C20/25 compressive strength class. Due to this reason the ζ multiplicator having the value originally 1.17 will take 1+0.7·0.17 = 1.12 new value.

An other example is that, in case of a concrete of C16/20 compressive strength class the concrete waste portion in the aggregate is in *Fr-B* physical group. Then in order to achieve the az $f_{cm,cube}$ = 25 N/mm^2 average compressive strength (*Table 4*) of the standard concrete cubes, which were wet cured (under water till the age of 28 days) must be designed to have a target mean strength (desired mean strength value) of $f_{cm,cube}$' = $\zeta \cdot f_{cm,cube}$ = 1.10·25 = 27.5 N/mm^2.

It is possible to diverge from the data given in *Table 5* if the experiments result in higher concrete compressive strength class then the desired one.

3.2 Design of light-weight concrete using recycled aggregate out of brick or mixed waste

In case of light-weight concrete, during the design process apart from the strength requirements appear the demands regarding the body density. During the mix design procedure the initial data to be taken into consideration are the properties of the light-weight waste aggregate.

The bulk strength of light-weight aggregate is to be determined according to the 1st process in appendix A of EN 13055-1:2002 and is to be expressed by the stress belonging to 20 mm compression (*Fig. 5*).

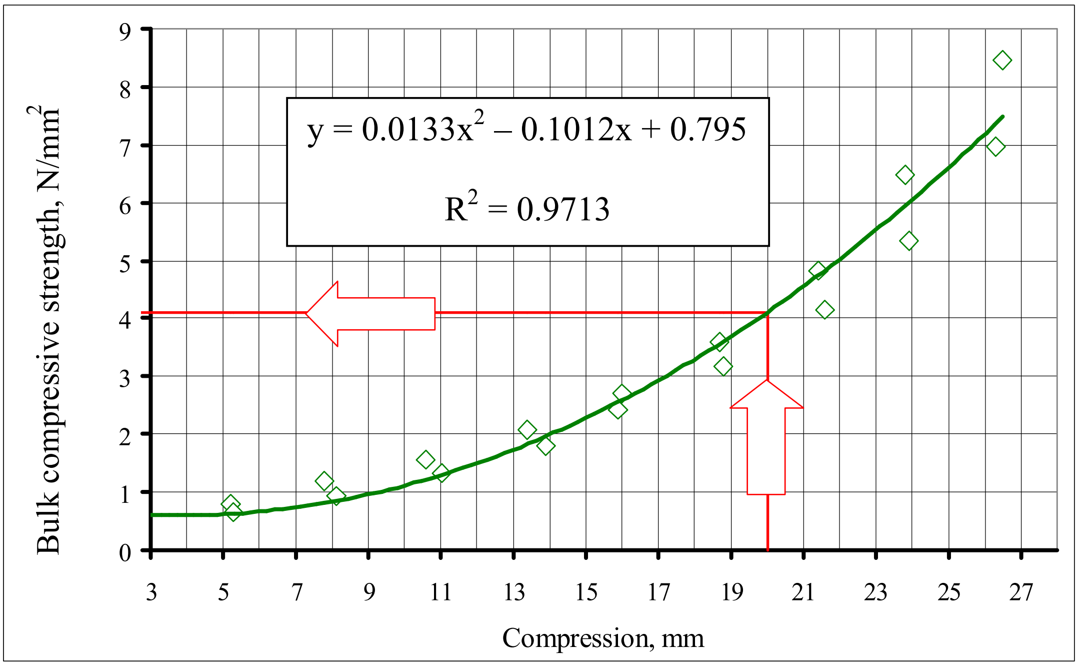


Fig. 5: Example to determine the bulk compressive strength of a light-weight aggregate

Even if in the light weight aggregate concrete the mortal is the main load carrier, still it is not practical to choose its strength much higher then that of the aggregate for uniform quality and being able to utilise the strength of the aggregate.

It is feasible to complement the light-weight aggregate with the fine component (generally below 1, 2, or 4 mm size) both from the point of durability and strength with natural sand. In this case the body densities of the applied aggregate types significantly differ due to what the grading curve may only be determined in volume percentages. In chase of the light-weight aggregate concrete when achieving the optimal strength the aim is not to achieve the saturated concrete state. In order to reach the practical load bearing capacity of light-weight aggregate concrete a minimum of 20 volume percent over-saturation of mortar is necessary. This is to be followed especially in case of an aggregate having a tabular particle shape which may easily occur in case of demolition, brick and mixed waste (*Nemes*, 2005).

Generally concretes out of recycled brick or mixed waste are to be designed as light-weight concrete. During the design process the body density and self strength of the brick waste are to be taken into consideration.

The brick or mixed waste cannot be classified into any physical group. Due to this reason the target mean strength of the light-weight recycled aggregate concrete can be obtained by multiplying the calculated mean compressive strength of the appropriate strength class (*Table 4*) by the $\eta_{light\text{-}weight}$ multiplicator (*Table 6*).

In case of wet curing the samples:

$f_{cm,cube,28,\ recycledconcrete} = \eta_{\ light\text{-}weight} \cdot f_{cm,cube}$

In case of mixed curing the samples (first 7days under water then at laboratory ambient circumstances):

$f_{cm,cube,H,28,\ recycledconcrete} = \eta_{\ light\text{-}weight} \cdot f_{cm,cube,H}$

The $\eta_{light\text{-}weight}$ multiplicator is a function of the compressive strength class (*Table 4*) of light-weight concrete according to *Table 6*.

It is possible to diverge from the data given in *Table 6* if the experiments result in higher light-weight concrete compressive strength class then the desired one.

Table 6: Strength multiplicator for the calculation of target mean strength of light-weight concrete at the age of 28 days *($\eta_{light\text{-}weight}$)*

Compressive strength class of light-weight concrete according to EN 206-1 standard $f_{ck,cyl} / f_{ck,cube}$	Values of $\eta_{light\text{-}weight}$ multiplicator
LC8/9 ρ_{LC} 2.0	1.50
LC12/13 ρ_{LC} 2.0	1.45
LC16/18 ρ_{LC} 2.0	1.40
LC20/22 ρ_{LC} 2.0	1.35
LC25/28 ρ_{LC} 2.0	1.30

4. DEFORMATION OF CONCRETE OUT OF RECYCLED AGGREGATE

4.1 Modulus of elasticity (E)

The *modulus of elasticity* (Young's modulus) of recycled aggregate concrete and light-weight concrete lags behind that of sandy gravel aggregate concrete.

According to the literature (*Grübl – Rühl,* 1998), if in the recycled concrete the quantity of the recycled particles which are bigger than 4 mm

- increases from zero (sandy gravel concrete) to 50 mass percent (recycled concrete), then the modulus of elasticity decreases by about 17.5 percent (from 34000 N/mm^2 to 28000 N/mm^2),
- increases from zero (sandy gravel concrete) to 100 mass percent (recycled concrete), then the modulus of elasticity decreases by about 20.5 percent (from 34000 N/mm^2 to 27000 N/mm^2),

The decrease of modulus of elasticity is also influenced by the compressive strength of the original concrete out of which the waste is originating. The waste having a lower self compressive strength decrease more the modulus of elasticity then the one having higher self compressive strength (*Siebel – Kerkhoff*, 1998).

According to *Meissner* (2000) the modulus of elasticity of recycled aggregate concrete is 10 – 40 percent lower and the deformation until failure is about 13 percent higher then that of concrete out of sandy gravel. It is reasonable to consider the modulus of elasticity of recycled concrete to a value of 20 percent lower then that of normal concrete.

According to the experiments of *Zilch* and *Roos* (2000) the modulus of elasticity of reference normal concrete, recycled aggregate of size more then 4 mm concrete and 100 percent recycled aggregate concrete is 33000 (100 percent), 26800 (81 percent) and 18200 (55 percent) N/mm^{2}respectively.

Recycled concrete out of *brick waste* has a significantly bigger decrease of modulus of elasticity compared to normal concrete then the one out of concrete waste (*Grübl – Rühl,* 1998). If the quantity of brick waste having bigger then 4 mm particle size in the recycled concrete

- increases from zero (sandy gravel concrete) to 50 mass percent (recycled concrete), then the modulus of elasticity decreases by about 32 percent (from 34000 N/mm^2 to 23000 N/mm^2),
- increases from zero (sandy gravel concrete) to 100 mass percent (recycled concrete), then the modulus of elasticity decreases by about 48.5 percent (from 34000 N/mm^2 to 17500 N/mm^2),

4.2 Shrinkage

The *shrinkage* of recycled aggregate concrete and light-weight concrete is bigger then that of sandy gravel aggregate concrete.

According to the literature (*Siebel – Kerkhoff*, 1998) the shrinkage of a concrete having 320 kg/m^3 cement content, 0,55 water-cement ratio, out of 100 percent recycled concrete aggregate at the age of 250 days nearly double (1.15 ‰) of that of the reference normal concrete (0.59 ‰). The modulus of elasticity of the aggregate significantly influences the shrinkage. The modulus of elasticity of concrete waste is proportional to its self compressive strength. Due to this reason it will decrease the shrinkage of recycled concrete aggregate concrete (0.90 ‰) if the self compressive strength of the recycled concrete aggregate increases.

According to the measurements of *Zilch* and *Roos* (2000) between the age of 7 – 50 days normal concrete dries faster then recycled concrete. Due to this reason the creep of recycled concrete in this time period is smaller then that of normal concrete, at the age of 50 days it is the same (about 0.3 ‰). Following this age the recycled concrete shrinks faster and at the age of 170 days the shrinkage of concrete made out of 100 percent from recycled aggregate is bigger by 58 percent (0.68 ‰) then that of normal concrete (0.43 ‰). If the particles smaller then 4 mm are out of sand, then the shrinkage of recycled concrete at the age of 170 days is only by 33 percent bigger (0.57 ‰) then that of normal concrete.

4.3 Creep

The *creep* of recycled aggregate concrete and light-weight concrete is bigger then that of sandy gravel aggregate concrete.

Based on the measurements of *Siebel* and *Kerkhoff* (1998) the creep of concrete made out of 100 percent recycled aggregate is 120 percent bigger then that of normal concrete.

According to the experiments of *Grübl* and *Rühl* (1998) 38 days following the loading, the creep factor of concrete out of 100 percent recycled concrete aggregate is bigger by 43 percent (0.97), concrete out of 100 percent recycled brick aggregate is bigger by 65 percent (1.12) then that of the reference normal concrete (0.68).

Meissner (2000), referring to the studies of *Grübl* and *Rühl* (1998) declares that the bigger creep of recycled concrete can be deduced to the bigger mortar content, the smaller modulus of elasticity and the higher water content of the demolition waste. To this is in connection that the long term strength of recycled concrete is only 80 percent of the normal concrete.

Zilch and *Roos* (2000) shows that while the creep factor at the age of 90 days of concrete out of recycled aggregate with particles bigger then 4 mm is 33 percent (3.6) bigger then that of the reference normal concrete (2.7), the creep factor of the 100 percent recycled aggregate concrete is already 210 percent bigger (8.4). This shows that to the change of the creep factor, the character of the particles (natural or recycled) smaller then 4 mm have significant influence.

5. PROPERTIES OF CONCRETE BLOCKS OUT OF DEMOLITION AND MATERIAL PRODUCTION WASTE

The composition of concrete used for the production of different type concrete blocks is to be designed in such a way that the measured mean compressive strength $f_{cm,cube,test}$ measured on standard cubes at the age of 28 days when they were wet cured and at the time of testing saturated with water should achieve $f_{cm,cube}$ according to the corresponding strength class. In case of mixed curing, at the time of testing air dry samples the measured mean compressive strength $f_{cm,cube,test,H}$ should achieve $f_{cm,cube,H}$ according to the corresponding strength class (*Table 6*).

Out of recycled demolition and construction waste aggregate concrete usually such blocks are produced which are listed in *Table 7*. In *Table 7* the exposure class X0b(H) is for concrete with no risk of corrosion, XK1(H) stands for low level wearing risk, XK2(H) is for medium level wearing risk, XK3(H) stands for high level wearing risk, XV1(H) is for low level watertightness in Hungary.

Table 7: Examples for the properties of blocks made out of recycled concrete

Sign of concrete according to MSZ 4798-1 Hungarian standard. Compressive strength class – exposure class – maximum size of aggregate in mm	Type of blocks made out of recycled demolition or construction waste	Compressive strength class according to the statical calculation	Exposure class according to EN 206-1 and to MSZ 4798-1 Hungarian standard	Strength class according to the exposure class	Considered	
					strength class	mean strength, according to *Table 4*, $f_{cm,cube,H}$ N/mm^2
Elements made out of normal-weight concrete						
C16/20–X0b(H)-8	Hollow, slab filling element	C16/20	X0b(H)	C12/15	C16/20	27
C12/15–X0b(H)–8	Hollow, formwork element	C8/10	X0b(H)	C12/15	C12/15	21
C16/20–X0b(H)–8	Hollow, cellar walling element, max. 54 % cavity volume	C16/20	X0b(H)	C12/15	C16/20	27
C12/15–X0b(H)–16	Hollow, load bearing, internal walling element, max. 32 % cavity volume	C12/15	X0b(H)	C12/15	C12/15	21
C30/37–XF1–16	Hollow, load bearing, external walling element, max. 32 % cavity volume	C12/15	XF1	C30/37	C30/37	49
C16/20–X0b(H)–16	Core concrete of double layered footpath tile with washed surface	C16/20	X0b(H)	C12/15	C16/20	27

C35/45–XF4, XK2(H)–16	Wearing concrete of double layered footpath tile with washed surface	C25/30	XF4, XK2(H)	C35/45	C35/45	60
C35/45–XF4, XK2(H)–16	Single layered footpath tile with washed surface	C25/30	XF4, XK2(H)	C35/45	C35/45	60
C35/45–XF4, XK2(H)–16	Single layered normal footpath tile	C20/25	XF4, XK2(H)	C35/45	C35/45	60
C35/45–XF4, XK2(H)–16	Footpath tile with lawn gaps	C20/25	XF4, XK2(H)	C35/45	C35/45	60
C25/30–X0b(H)–24	Core concrete of double layered pavement tile	C25/30	X0b(H)	C12/15	C25/30	40
C40/50–XF4, XK3(H)–24	Wearing concrete of double layered pavement tile	C35/45	XF4, XK3(H)	C40/50	C40/50	67
C40/50–XF4, XK3(H)–24	Single layered pavement tile	C35/45	XF4, XK3(H)	C40/50	C40/50	67
C35/45–XF4, XK2(H)–24	Normal curb element	C16/20	XF4, XK2(H)	C35/45	C35/45	60
C40/50–XF4, XK3(H)–24	Wear resistant curb element	C30/37	XF4, XK3(H)	C40/50	C40/50	67
C30/37–XF1, XV1(H)–24	Watercourse tile	C25/30	XF1, XV1(H)	C30/37	C30/37	49
C30/37–XF1, XV1(H)–16	Watercourse covering element	C30/37	XF1, XV1(H)	C30/37	C30/37	49
C30/37–XF1, XV1(H)–16	Reinforced watercourse element, hopper element	C30/37	XF1, XV1(H)	C30/37	C30/37	49
Elements made out of light-weight concrete						
LC12/13–ρ_{LC} 1,8 –X0b(H)–8	Hollow, formwork element	LC12/13	X0b(H)	LC8/9	LC12/13	19
LC16/18–ρ_{LC} 1,8 –X0b(H)–8	Hollow, cellar walling element, max. 54 % cavity volume	LC16/18	X0b(H)	LC8/9	LC16/18	24
LC16/18–ρ_{LC} 1,8 –X0b(H)–8	Hollow, load bearing, internal walling element, max. 32 % cavity volume	LC16/18	X0b(H)	LC8/9	LC16/18	24
LC25/28–ρ_{LC} 1,8 –XF1–8	Hollow, load bearing, external walling element, max. 32 % cavity volume	LC16/18	XF1	LC25/28	LC25/28	35
LC12/13–ρ_{LC} 1,8 –X0b(H)–32	Dense, load bearing, internal walling element	LC12/13	X0b(H)	LC8/9	LC12/13	19
LC25/28–ρ_{LC} 1,8 –XF1–32	Dense, load bearing, external walling element	LC12/13	XF1	LC25/28	LC25/28	35

LC25/28–ρ_{LC} 1,8 –XF1– 8	External, heat insulating walling element	LC8/9	XF1	LC25/28	LC25/28	29
LC12/13–ρ_{LC} 1,8 –X0b(H)–8	Hollow, partition walling element, max. 45 % cavity volume	LC12/13	X0b(H)	LC8/9	LC12/13	19
LC25/28–ρ_{LC} 1,8 – XK1(H)– 16	Internal floor tile	LC20/22	XK1(H)	LC25/28	LC25/28	35

6. CONCLUSIONS

During the production and the design of composition of recycled normal-weight and light weight concrete, unlike during the usual methods, also must be taken into consideration the fragmentation, bulk strength, frost resistance, water absorption and particle shape of the aggregate. The target design compressive strength of recycled concrete may be expressed in the function of the physical properties of the demolition waste aggregate.

Laboratory test results and industrial test production of concrete blocks proved that, out of concrete waste – originating from demolition – simple concrete blocks can be produced in good quality, which satisfy the density, the compressive strength and the durability requirements. Mixed waste is mainly suitable for producing light-weight concrete elements for indoor usage.

The Technical guideline for concrete and reinforced concrete, prepared by the Hugarian group of *fib* contributes to that demolition, construction and material production waste can be recycled as concrete aggregate under controlled circumstances with good results in Hungary.

7. NOTATIONS

C.../...	Compressive strength classes in case of normal-weight concrete
CEM...	Cement type according to the series EN 197
d	Minimum nominal size of aggregate, mm
D	Maximum nominal size of aggregate, mm
$f_{ck,cyl}$	Characteristic compressive strength of concrete determined by testing standard cylinders, after wet curing
$f_{ck,cube}$	Characteristic compressive strength of concrete determined by testing standard cubes, after wet curing
$f_{cm,test}$	Experienced mean compressive strength of concrete at the age of 28 days, measured on standard samples
$f_{cm,cube}$	Required mean compressive strength of concrete measured on standard cubes at the age of 28 days, which were wet cured, in N/mm^2
$f_{cm,cube,H}$	Required mean compressive strength of concrete measured on standard cubes at the age of 28 days, which were mixed cured, in Hungary, in N/mm^2
$f_{cm,cube,recycledconcrete}$	Target design compressive strength of concrete out of recycled concrete (possibly mixed concrete/brick) waste, as the required mean compressive strength of concrete measured on standard cubes at the age of 28 days, which were wet cured, in N/mm^2

$f_{cm,cube,H,\ recycledconcrete}$	Target design compressive strength of concrete out of recycled concrete (possibly mixed concrete/brick) waste, as the required mean compressive strength of concrete measured on standard cubes at the age of 28 days, which were mixed cured, in Hungary, in N/mm^2
$f_{cm,cube,test}$	Experienced mean compressive strength of concrete at the age of 28 days, wet cured and measured on standard cube samples, in N/mm^2
$f_{cm,cube,test,H}$	Experienced mean compressive strength of concrete at the age of 28 days, mixed cured and measured on standard cube samples, in Hungary, in N/mm^2
$f_{cm,cyl}$	Required mean compressive strength of concrete measured on standard cylinders at the age of 28 days, which were wet cured, in N/mm^2
Fr-…	Physical group of recycled concrete and normal-weight mixed concrete/brick waste aggregates in Hungary
LC.../...	Compressive strength classes in case of light-weight concrete
m_v	Water dosage in 1 m^3 compacted fresh concrete, which is the sum of $m_{v,0}$ basic amount and the $m_{v,\Delta}$ extra amount of mixing water, in kg/m^3
$m_{v,0}$	Quantity of basic mixing water dosage in 1 m^3 compacted fresh concrete, the value of which is the product of the designed water-cement ratio and cement dosage, in kg/m^3
$m_{v,\Delta}$	Extra amount of mixing water dosage, which can be calculated from the short term water absorption capacity of the aggregate in 1 m^3 compacted fresh concrete, in kg/m^3
X0b(H)…	Exposure class for no risk of corrosion in Hungary
XF…	Exposure classes for freeze/thaw attack
XK…(H)	Exposure classes for wear resistance in Hungary
XV…(H)	Exposure classes for watertightness requirement in Hungary
ρ_τ	Symbol of body density in Hungary
ρ_h	Symbol of bulk density in Hungary
ζ	Multiplicator to calculate the design target mean compressive strength of recycled aggregate normal-weight concrete at the age of 28 days
$\eta_{light\text{-}weight}$	Multiplicator to calculate the design target mean compressive strength of recycled mixed and brick aggregate light-weight concrete at the age of 28 days

8. REFERRED STANDARDS AND TECHNICAL GUIDE

MSZ 4798-1:2004 „Concrete. Part 1: Specification, performance, production, conformity, and rules of application of MSZ EN 206-1 in Hungary"

MSZ 18288-2:1984 „Building rock materials. Test for granulometric composition and impurity. Part 2: Test of settling"

MSZ 18288-4:1984 „Building rock materials. Test for granulometric composition and impurity. Part 2: Test of chemical impurity"

EN 206-1:2000 „Concrete. Part 1: Specification, performance, production, conformity, and rules"

EN 933-1:1997 „Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method"

EN 933-4:1999 „Tests for geometrical properties of aggregates. Part 4: Determination of particle shape. Shape index"

EN 933-6:2001 „Tests for geometrical properties of aggregates. Part 6: Determination of particle shape. Flakiness index”

EN 1097-3:1998 „Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids”

EN 1097-6:2000 „Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption”

EN 1367-1:2007 „Tests for thermal and weathering properties of aggregates. Part 1: Determination of resistance to freezing and thawing”

EN 1367-2:1999 „Tests for thermal and weathering properties of aggregates. Part 2: Magnesium sulphate test”

EN 12620:2002 „Aggregates for concrete”

EN 13043:2002 „Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas”

EN 13055-1:2002 „Lightweight aggregates. Part 1: Lightweight aggregates for concrete, mortar and grout”

EN 13139:2002 „Aggregates for mortar”

BV-MI 01:2005 „Production of concrete using demolition, construction and material production recycled waste” in Hungarian, Hungarian technical guideline of concrete and reinforced concrete production, Hungarian group of ***fib***

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