PhD thesis

Early age shrinkage cracking tendency of concretes

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1. RESEARCH SIGNIFICANCE AND LITERATURE REVIEW

In concrete, mortar and cement paste shrinkage takes place from the very beginning of the life of the material. The volume change can be both swelling and shrinking in early age, but later ***shrinkage*** will be relevant, which is caused by water movement in the porous and rigid body. During the hydration of cement (in the first 2-8 hours), while the cement paste is plastic, it undergoes a volumetric contraction (***plastic shrinkage***), while in cement paste as in any other fine-grained suspension, water move toward the external surface of the specimen. After compaction and consolidation of particles the water is withdrawn from the capillary pores towards the external surface due to its surface tension and evaporated (so that this deformation is also called capillary shrinkage). Volume reduction of the outer layer is inhibited by the inner part of the material, and this can result map-like, wide cracks, so-called mapping (the same as fine mud forms cracks after drying) *[Lägel et al.]*. Cement paste has a volume change also during the hydration (***autogenous shrinkage***), due to the less volume of the hydration products (cement stone) compared to the initial volume of cement + water. However, the extent of hydration prior to setting is small, and once a certain stiffness of the system has developed, the contraction induced by the loss of water by hydration is greatly restrained *[Neville, 1995]*. Withdrawal of water from hardened concrete, mortar or cement paste stored in unsaturated air causes ***drying shrinkage***. A part of this drying shrinkage is irreversible and should be distinguished from the reversible moisture movement caused by alternating storage under wet and dry condition *[Neville 1995, Grube 2003]*. Plastic, autogenous and drying shrinkage together are called early age shrinkage.

Influencing factors of early age shrinkage in mix design:

- cement content of the paste
- specific surface area of cement
- fine aggregate content (under 0.125 mm particle size)
- specific surface area of fine aggregate
- water-cement ratio
- total aggregate content
- type of aggregate
- water absorption capacity and water content of aggregate
- applied admixtures
- compacting rate of paste
- porosity
- other added components e.g. fibres.

Shrinkage of concrete depends on the temperature of concrete and its surrounding, the relative humidity and the velocity of air movement as well as the curing and composition of the concrete *[Neville 1995]*.

Drying shrinkage related to the most important mix parameters of concrete was studied by *Grube, 2003*. He found that the most important influencing parameters to shrinkage are: cement content, type of cement, and water content (*Fig. 1.*).

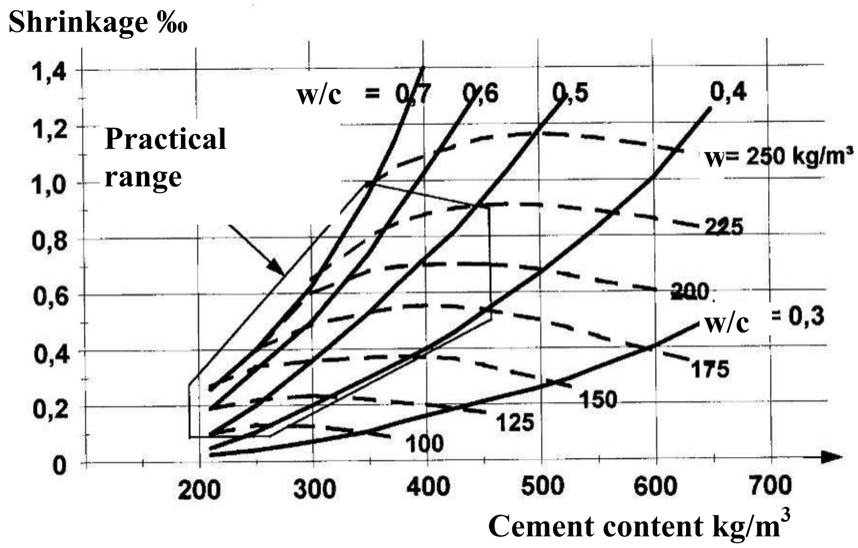


Fig. 1. Drying shrinkage related to cement content and water-cement ratio [Grube 2003]

It is often a problem during the design and construction of concrete and reinforced concrete structures to meet the requirements of crack-free structures, e.g. exposed concretes, hydraulic engineering works, gas-tight, watertight or liquid-tight concretes. Crack formation is also disadvantageous in the point of view of durability.

Time has a two-fold effect from this sense: the strength increases with the hydration, thereby reducing the cracking tendency, but on the other hand, the stress induced by shrinkage also increases by the increase of the Young's modulus. If stress reaches the tensile strength of concrete, cracks appear on the structure or specimen (*Fig. 2.*) *[Neville 1995]*.

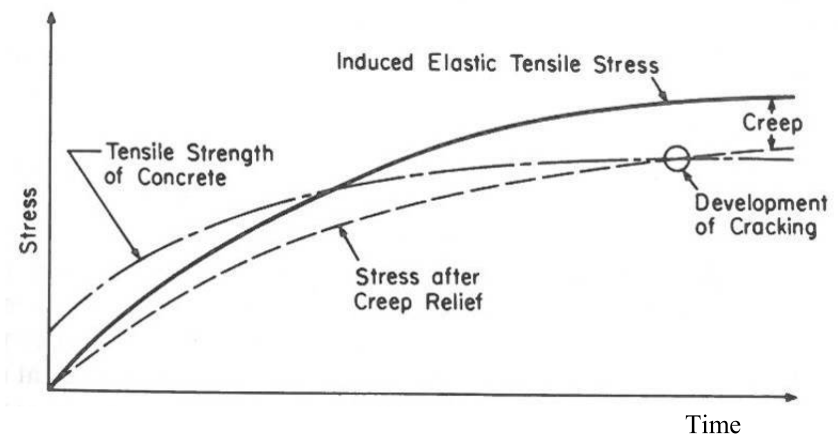


Fig. 2. Relationship between tensile strength and shrinkage induced tensile stress *[Neville 1995]*

2. AIM OF THESIS

Relatively few data are available considering the early age shrinkage cracking tendency of concretes, especially in case of ***lightweight aggregate concretes*** (LWAC). Nowadays increasing number of lightweight aggregate types are available in Hungary, and we do not know their influence on the early age shrinkage cracking tendency, however it is a common question during the mix design. In case of ***fibre reinforced concretes*** (FRC) new types of fibres are fabricated for FRC from different raw materials. Polymer and glass fibres are applied to prevent early age shrinkage crack formation, so it is important to know their effects (and side effects too) (in my thesis steel fibres are not discussed). It is a common question of crack-free concrete mix design to choose the ***cement type***, and to know which parameters of cement are required for reduced cracking tendency of concrete.

Aims of thesis:

- determination of early age shrinkage cracking tendency of *LWACs* according to the water absorption capacity of lightweight aggregate;
- determination of early age shrinkage cracking tendency of *FRCs* according to the applied fibre type and dosage;
- determination of early age shrinkage cracking tendency of *normal concretes* according to the applied *cement type*.

Internal curing effect is an important parameter in case of LWACs, which slows down drying procedure of concrete, therefore, it can influence the extent of drying shrinkage too. The water absorption of the aggregate also reduce the effective water cement ratio in cement paste so can increase the strength of cement stone. The internal curing effect is related to water absorption and open pore structure of lightweight aggregates. In my thesis I investigate how much internal curing effect can reduce early age shrinkage cracking tendency of LWAC.

In case of FRCs the two most important mix design parameters are ***fibre type*** and ***dosage***. In my research different types of short and thin polymer and glass fibres fabricated for FRC were investigated (steel fibres were not investigated). The results help to apply the optimal fibre type and dosage during the mix design.

Early age shrinkage cracking tendency has high priority during the construction of several reinforced concrete structures (exposed concretes, basins, water towers, gas containers, waterproof concretes, waterworks structures, and flat roofs). Based on present scientific results it can be chosen the right cement type during the mix design of these structures.

3. EXPERIMENTAL STUDIES

A mixture recipe was used for the experimental studies of crack tendency, which is very sensitive to early age (in the first three days) shrinkage cracking, so the investigated test parameters could have been precisely compared. The basic mixture is given in an Austrian technical specification *[Richtlinie Faserbeton 2002 and 2008]*. Neat Portland cement has the most intense setting performance, so it has the highest early age shrinkage, if the water-cement ratio is constant *[Balázs et al. 1979]*. Therefore CEM I 42,5 N cement was used (except when cement types were compared). The mixture contained high volume (500 kg/m^3) of fine particles (size under 0.125 mm) from wich cement was 360 kg/m^3 and the rest was limestone dust). The water-cement ratio was 0.61, and the water content was 220 l/m^3.

The technical specification *[Richtlinie Faserbeton 2002]* also describes a test method for which special ring specimens are needed (four specimens for each mixture) (*Fig. 3.*) To the inner side of the outer formwork 12 pieces of 40×40 mm size steel plates are welded, to increase cracking tendency of the specimen. The experiment has to be carried out in a climate chamber of 65 % relative humidity and 20 °C temperature. To evaluate early age shrinkage cracking tendency of the mixtures the length of every crack is to be summarized. Another method is proposed whereby the crack length is multiplied with the crack width and the values are added to each other. During my research programme 124 concrete mixtures and 42 cement pastes were investigated, which means cca. 700 pieces of ring specimens and 1200 pieces of other types of specimens. On every ring specimen crack lengths were measured on each sides (in most cases crack widths were also measured).

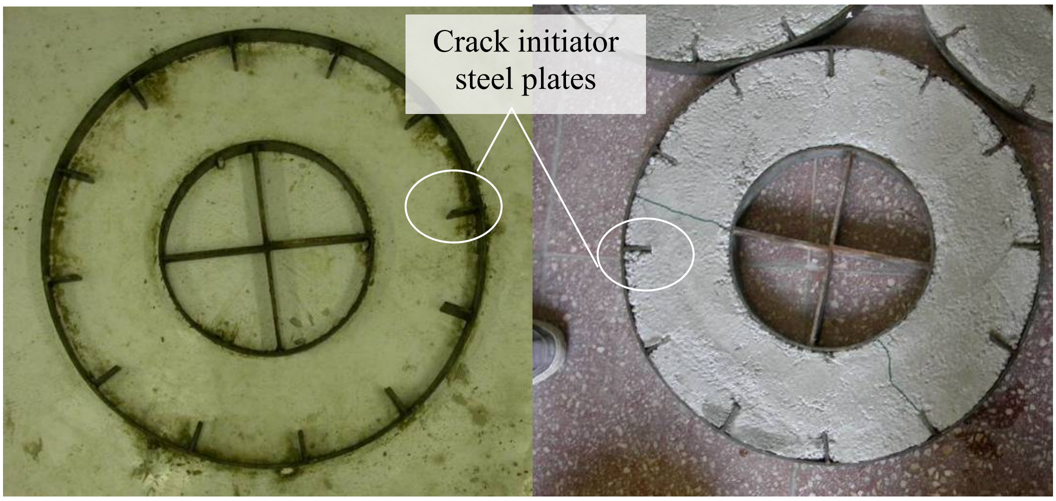


Fig. 3. Empty (left) and filled (right) formworks for measuring crack tendency

As I have experienced, that ring specimens did not dry out during testing of 5 hours according to the Austrian technical specification, so they were stored in a tumbler-drier for two further days at a temperature of 60 °C to achieve improved drying, after which additional cracks were registered on the specimens. During this drying method both sides of the specimen could be dried, and the temperature was higher compared to the wind tunnel, so the drying has higher intensity. The most important test methods are summarized in *Tab. 1.*

Tab. 1. The most important test methods during the research programme

Measured property	Type of specimen	Duration/age	Volume/mixture	Method
Specific surface area	Cement	-	3×5-10 g	Blaine (air permeability) method
Compressive strength	Cement mortar prism, 40×40×160 mm	28 days age	3 specimen	Compression test
Compressive strength	Cementstone prism, 40×40×160 mm	2; 7; 28 and 90 days age	3 specimen	Compression test
Shrinkage	Cementstone prism, 40×40×160 mm	1-180 days	3 specimen	Graf-Kaufmann test
Water absorption	Aggregate bulk	0.5 and 24 hours age	0.5 litre	Mass weight
Particle body density	Aggregate bulk	-	0.5 litre	Mass weight
Fresh concrete body density	Concrete cube, 150×150×150 mm	15 minutes age	3 specimen	Mass weight
Consistency	-	10 minutes age	-	Flow table test
Compressive strength	Concrete cube, 150×150×150 mm	28 days age	3 specimen	Compression test
Flexural tensile strength	Concrete prism, 70×70×250 mm	1 and 3 days age	3 specimen	Flexural tensile test
Early age cracking tendency	Concrete ring, ø600/300×40 mm	5 hours long	4 specimen	Wind drying
Early age cracking tendency	Concrete ring, ø600/300×40 mm	48 hours long	4 specimen	Ordinary drying at 60 °C
Early age cracking tendency	Cement stone ring, ø240/160×40 mm	Until cracking	3 specimen	Cracking time

During the investigation of the early age shrinkage cracking tendency of different cement types, the variable parameter was the cement type. 13 cement types were investigated, D1-4 indicate pure portland cements, D5-11 indicate CEM II blended cements, and D12-13 indicate CEM III blended cements. Beside the cracking tendency compressive strength of the concrete mixtures were determined according to the standard MSZ 4798-1, and flexural tensile strength was measured on concrete prism specimen made with 0,45 and 0,55 water-cement ratio. With the same cement samples cement stone and cement mortar mixtures were prepared and their compressive strength were tested at the age of 2, 7 and 28 days according to the standard MSZ EN 196-1:2005. Early age shrinkage was also measured on cement pastes at 2 days age.

After the testing of the concrete ring specimens cement stone ring specimens were tested with the same cross-section 40×40 mm as at the compressive strength test, the outer diameter of the ring specimen was 240 mm, and the inner diameter was 160 mm. The cement paste is poured around a rigid steel core and early age shrinkage tensile stresses are induced in the ring specimen. If the tensile stresses became higher than the tensile strength of the cement stone, a crack is formed. The cracking tendency was indicated with the time to cracking. The early age shrinkage cracking tendency of different cement types were investigated by the two test methods.

During my research several lightweight aggregate types (from several producers) were investigated. Water absorption, particle body density and bulk density were tested according to the standard MSZ EN 13055-1:2003 (*Tab. 2.*). The variable parameter was the type of coarse aggregate (4/8 fraction). The fine (0/4) fraction was quartz sand in every mixture.

Tab. 2. Main technical parameters of the lightweight aggregates applied for the LWAC tests

Aggregate	Particle body density [kg/m^3]	Water absorption [m%]	
		0.5 hour	24 hours
Quartz gravel	2670	0	0
Expanded glass 1	1320	1.4	1.8
Expanded glass 2	290	12	23
Expanded glass 3	949	6.1	8.2
Expanded clay	1247	8	13
Crushed clay brick	1682	17	19
Expanded perlite	220	~200	~200
Polystyrene	96	0	0

Fibres were added to the mixture one minute before the water addition for better mixing. Variable parameters were the dosage and the type of fibres. Main parameters of these fibres are summarized in Table 1. During the research thin (9÷20 μm diameter) and short (5÷35 mm long) polymer and glass fibres were used. The tensile strength of the fibres is higher than the tensile strength of early age concrete, so they can resist against tensile stresses caused by shrinkage. The Young's modulus of the fibres were different, glass has 70 000 N/mm^2, and the polymer fibres have 1000 or 7000 N/mm^2.

4. NEW SCIENTIFIC RESULTS OF PRESENT RESEARCH

Bold text indicate the new scientific conclusions, other parts introduce or interprete them.

4.1 Cracking tendency of lightweight aggregate concretes [1, 3, 6]

Drying shrinkage of lightweight aggregate concretes is reduced as water absorption capacity is increasing of the lightweight aggregate because of the internal curing effect. Water absorption of aggregate also reduce the effective water-cement ratio, which increases tensile strength of concrete.

I have experimentally shown, that the relationship between the 24 hours water absorption capacity (V%) of expanded glass, expanded clay, expanded perlite and quartz gravel aggregates and the early age shrinkage cracking tendency of LWAC is almost linear. If the water absorption of lightweight aggregate is increasing the cracking tendency of LWAC is decreasing *(Fig. T1-T2.)***.**

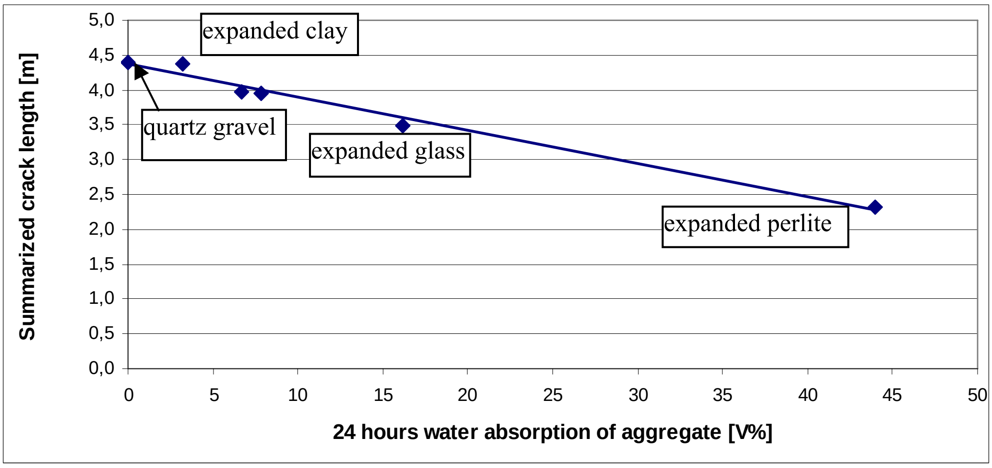


Fig. T1. Relationship between 24 hours water absorption of aggregate and summarized crack length of LWACs after the two (wind tunnel and tumbler dryer) tests (every point indicates the average result of 4 specimens)

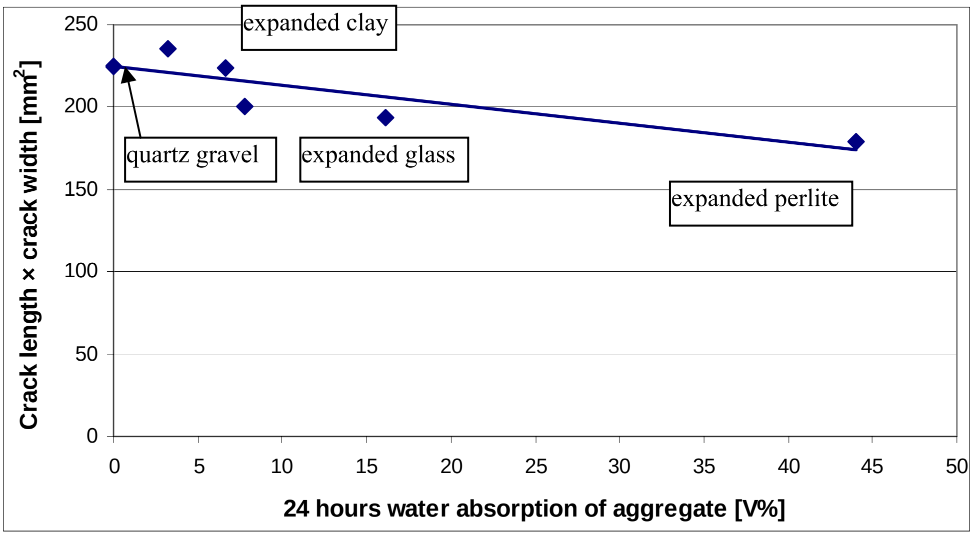


Fig. T2. Relationship between 24 hours water absorption of aggregate and summarized crack length × crack width of LWACs after the two (wind tunnel and tumbler dryer) tests (every point indicates the average result of 4 specimens)

4.2 Crack tendency of fibre reinforced concretes

4.2.1. [2, 5, 9, 11]

Thin and short polymer and glass fibres can effectively reduce the early age shrinkage cracking tendency of concrete due to their high tensile strength and their high specific bond interface. **I have experimentally shown, that the relationship between fibre content of FRC (between 0÷1.5 kg/m^3) and early age shrinking cracking tendency of FRC is almost linear in case of thin (9÷20 µm) and short (5÷35 mm long) polymer and glass fibres (***Fig. T3-5.***).**

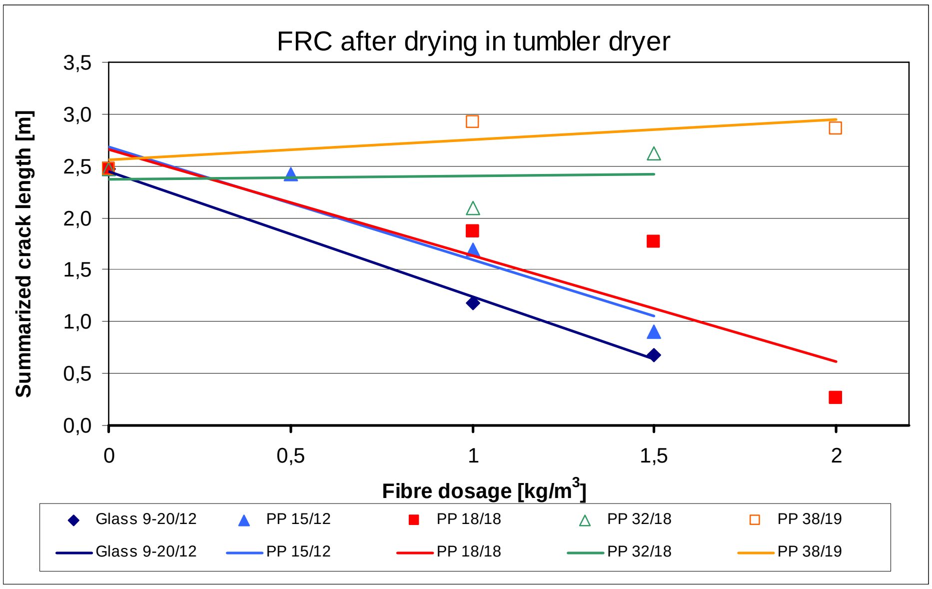


Fig. T3. Relationship between early age shrinkage cracking tendency (average summarized crack lengths of four specimens) of FRC after curing in tumbler drier and the fibre dosage

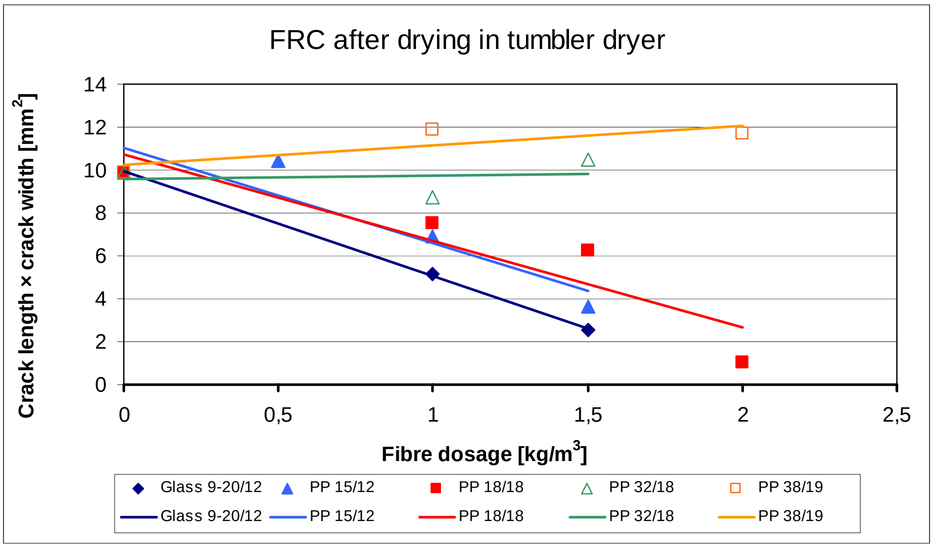


Fig. T4. Relationship between early age shrinkage cracking tendency (summarized crack lengths × crack width, average of four specimens) of FRC after curing in tumbler drier and the fibre dosage

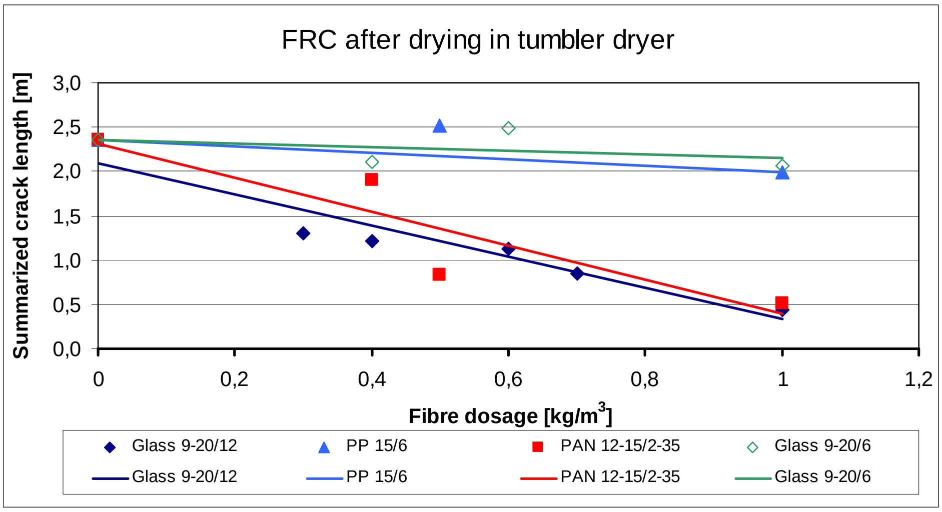


Fig. T5. Relationship between early age shrinkage cracking tendency (average summarized crack lengths of four specimens) of FRC after curing in tumbler drier and the fibre dosage

4.2.2. [2, 5, 9, 11]

I have experimentally shown that the linearity of the relationship between the early age shrinkage cracking tendency and the fibre dosage of a fibre type measured with several different reference mixtures does not change, only the starting point of the lines of the different mixtures changes. The effectiveness of a fibre type can be indicated by the gradient (firstderivative) of the line. (*Fig T7.*). The reason is the following: if the cracking tendency of the reference mixture (without fibres) is changed (cement dosage, fine aggregate content, aggregate size distribution, cement type (specific surface, composition)), cracking tendency of all the other mixtures of the measurement series will change. Therefore the test results could not be compared with a previous measurement from an other series, but comparison of two test series (with several different fibre dosages) can be done.

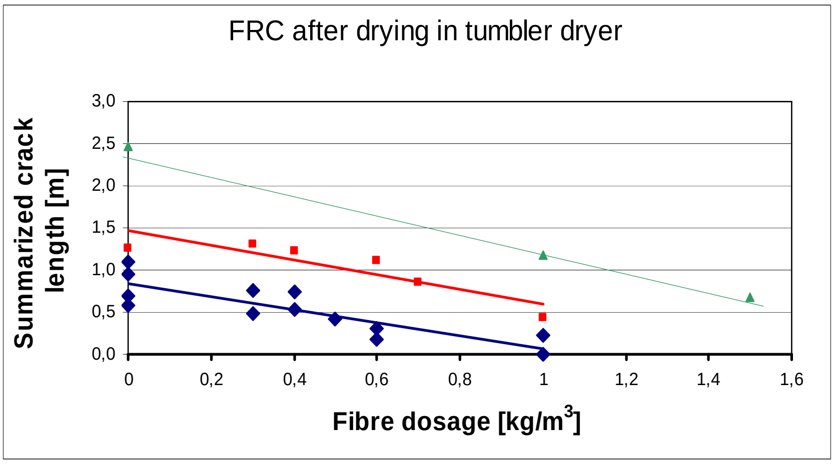


Fig. T7. Relationship between early age shrinkage cracking tendency of glass fibre reinforced concretes (average summarized crack lengths of four specimens) after curing in tumbler drier and the fibre dosage with different cracking tendency of reference mixtures (made without fibres)

4.2.3. [2]

I have experimentally shown that the crack reducing effectiveness of the fibre type is depending on the aspect ratio of the fibre (l/ø; fibre length [mm] / fibre diameter [µm]). Fibres with higher aspect ratio than 800 mm/µm can effectively reduce cracking tendency of concrete, and fibres below 600 mm/µm can not (*Fig. T6.,Tab. T1.*). Too short, 6 mm long fibres reduce crack formation with low efficiency, because they can not resist against tensile stresses due to the short bond length. Fibres with high diameter can not utilize a high part of their load bearing capacity, because the bond strength between the fibre and the concrete is reached before the tensile stresses could reach the tensile strength of the fibre. Investigating fibres with high diameter I have experienced that the summarized crack length increased with the fibre dosage, wich was a result of the higher porosity of FRC compared to normal concrete.

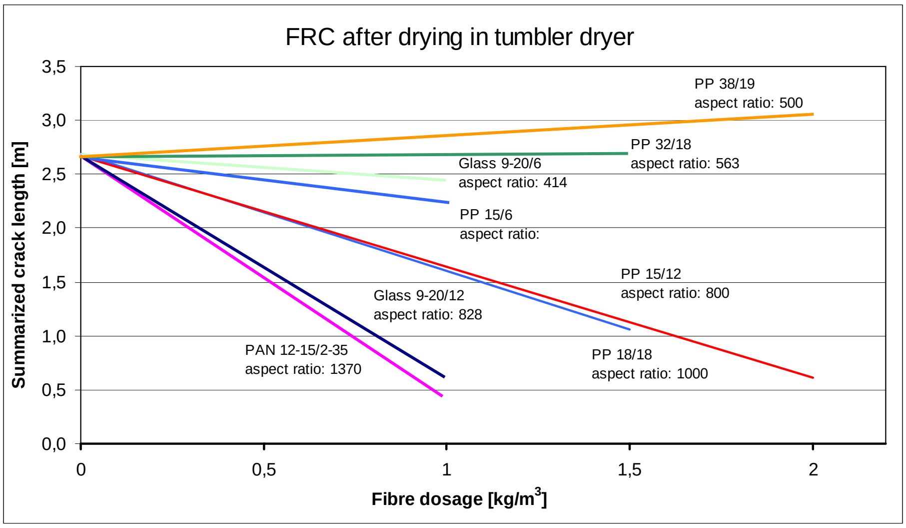


Fig. T6. Relationship between effectiveness of reducing early age shrinkage cracking tendency (average summarized crack lengths of four specimens) of fibres and the fibre aspect ratio

Tab. T1. Properties of used fibres sorted by aspect ratio and crack reducing effectiveness

Fibre type	Material	Diameter [μm]	Length [mm]	Aspect ratio ℓ/ø [-]	Young's modulus [N/mm²]	Tensile strength [N/mm²]	Effectiveness of crack length reduction by fibre dosage [m/kg/m³]
Glass 9-20/6	E-glass	9÷20	6	414	70 000	2000	-0,21
PP 15/6	PP	15	6	400	1000	200	-0,36
PP 38/19	PP	38	19	500	1000	400	0,20
PP 32/18	PP	32	18	563	1000	300	0,03
PP 15/12	PP	15	12	800	1000	200	-1,09
Glass 9-20/12	E-glass	9÷20	12	828	70 000	2000	-1,77
PP18/18	PP	18	18	1000	1000	200	-1,02
PAN 12-15/2-35	PAN	12÷15	2÷35	1370	7000	400	-1,91

4.3 Cracking tendency of cementitious materials with different cement types

4.3.1.

I have experimentally shown that the relationship between the cracking time of the tested cement pastes and the early age compressive strength (at the age of 2, 7 and 28 days) of the cement pastes and the compressive strength of the standard cement mortars is almost linear (*Fig. T8-9.*). The higher is the compressive strength the lower is the cracking time, which indicates higher early age shrinkage cracking tendency.

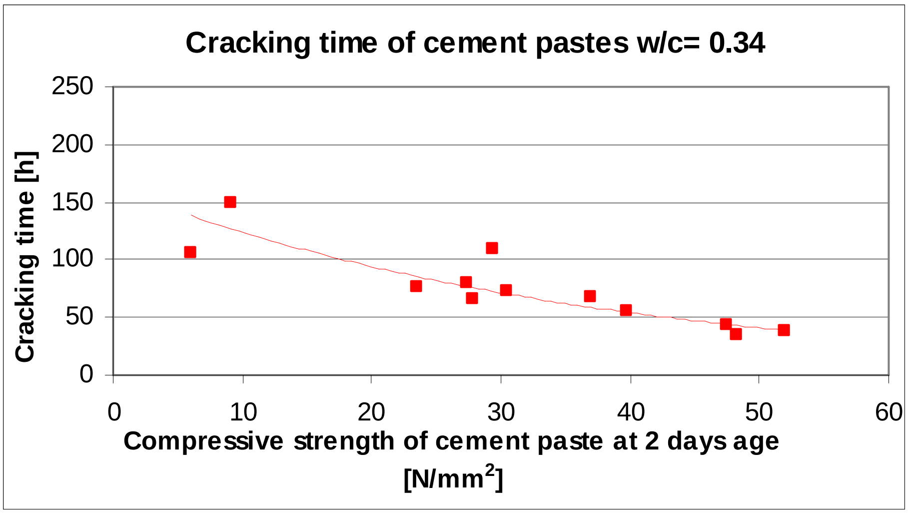


Fig. T8. Relationship between cracking time of the cement paste rings and the compressive strength of the cement paste prisms at the age of 2 days (average of three specimens, w/c = 0.34)

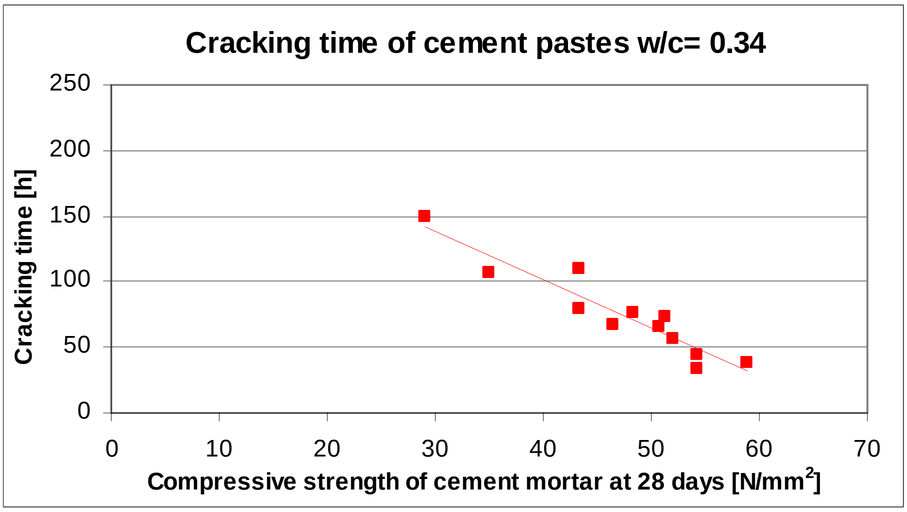


Fig. T9. Relationship between cracking time of the cement paste rings (average of three specimens, w/c = 0.34) and the compressive strength of the cement mortar prisms at the age of 28 days (average of three specimens, w/c = 0.50)

4.3.2

I have experimentally shown that the relationship between the cracking time and the rate of hardening of the cement pastes which can be indicated by the compressive strength rate at 2/7 days and 2/28 days is almost linear (*Fig. T10.*). The higher is the rate of hardening, the lower is the cracking time, which indicates higher early age shrinkage cracking tendency.

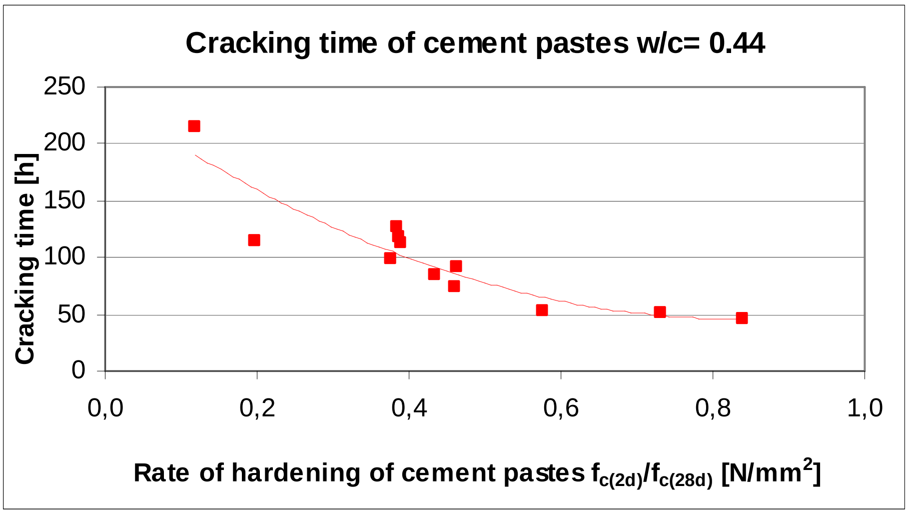


Fig. T10. Relationship between cracking time of the cement paste rings (average of three specimens, w/c = 0.44) and the rate of hardening of the cement paste prisms at the age of 2days/28 days (average of three specimens, w/c = 0.44)

4.3.3.

I have experimentally shown that the relationship between the cracking time and the early age shrinkage (at the age of 2 days) of the tested cement pastes is almost linear (*Fig. T11.*). The higher is the early age shrinkage the lower is the cracking time, which indicates higher early age shrinkage cracking tendency.

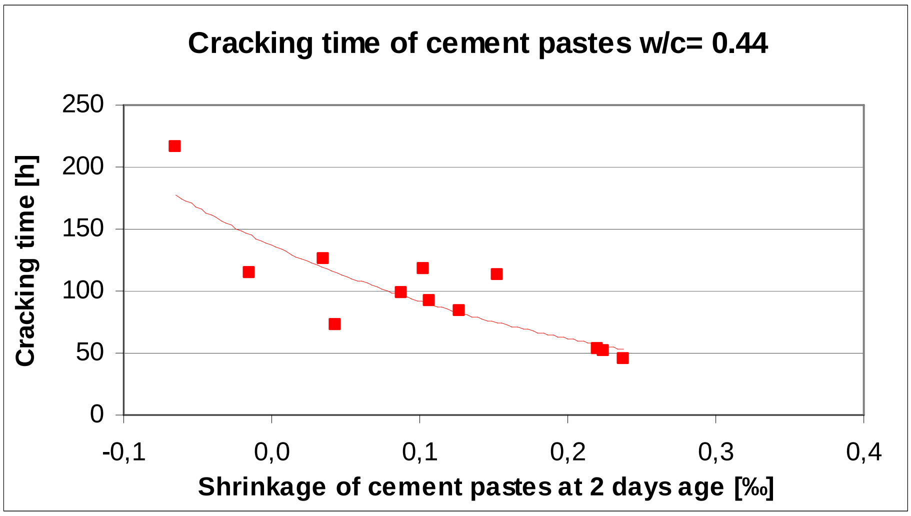


Fig. T11. Relationship between cracking time of the cement paste rings (average of three specimens, w/c = 0.44) and the shrinkage of cement paste prisms at the age of 2days (average of three specimens, w/c = 0.44)

4.3.4.

I have experimentally shown that there is a relationship between the early age shrinkage cracking tendency of the tested concretes and the early age flexural tensile strength (at the age of 1 and 3 days), the standard compressive strength of the concretes, the compressive strength of the standard cement mortars and early age compressive strength of the cement pastes (at the age of 2 days). Increasing specific surface (fineness) of cement increases the cracking tendency. Sorting cement types by the early age shrinkage cracking tendency of concretes indicating the influencing parameters in percents (highest parameter value is 100%, the lowest is 0%), it can be seen, that summarized crack length and the crack area are decreases with the parameters mentioned above **(Figs. *T12-19.*)**. D5-11 indicate CEM II blended cements, and D12-13 indicate CEM III blended cements.

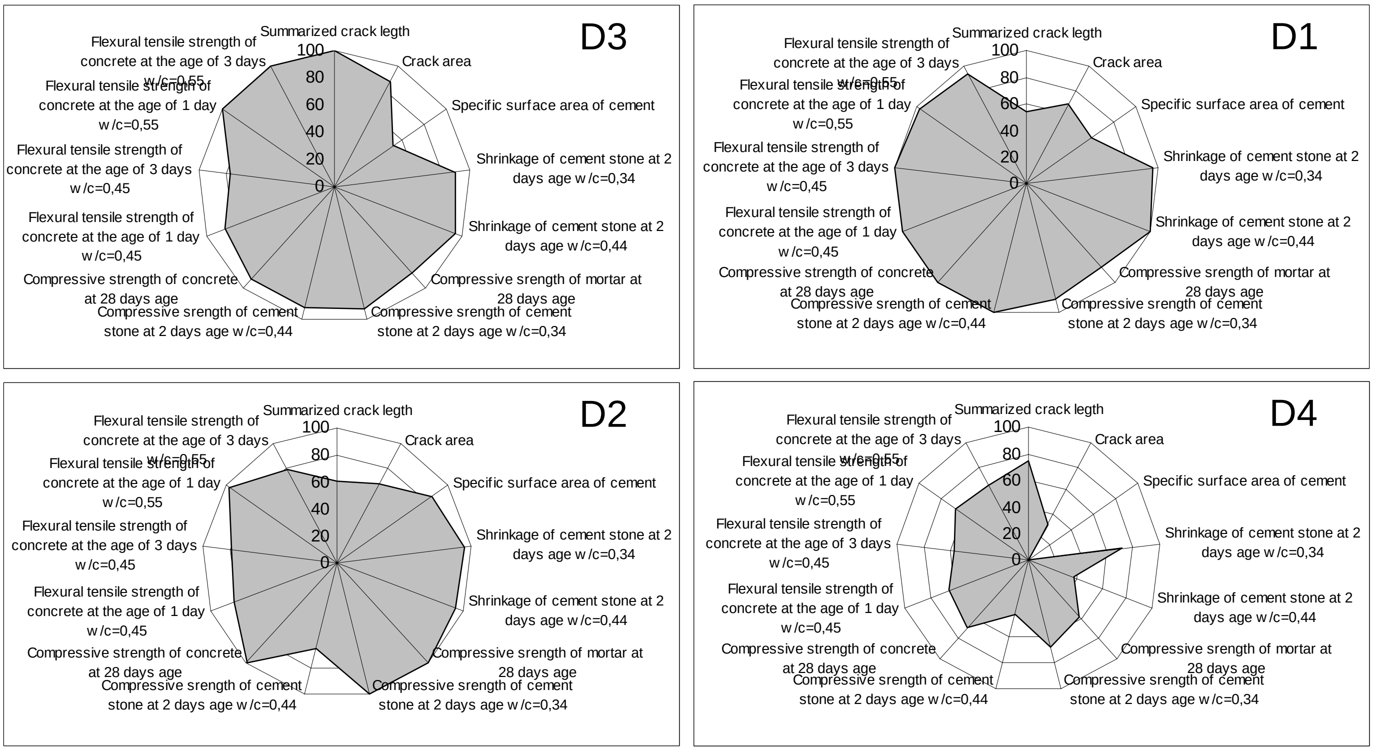
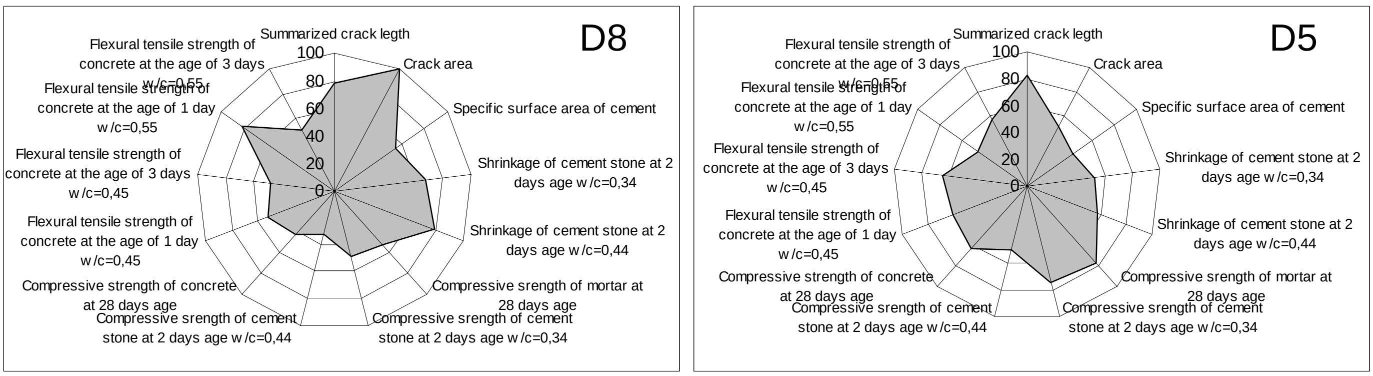


Fig. T12. Relationships between CEM I cement type, and crack length and crack area sorted by the early age shrinkage cracking tendency



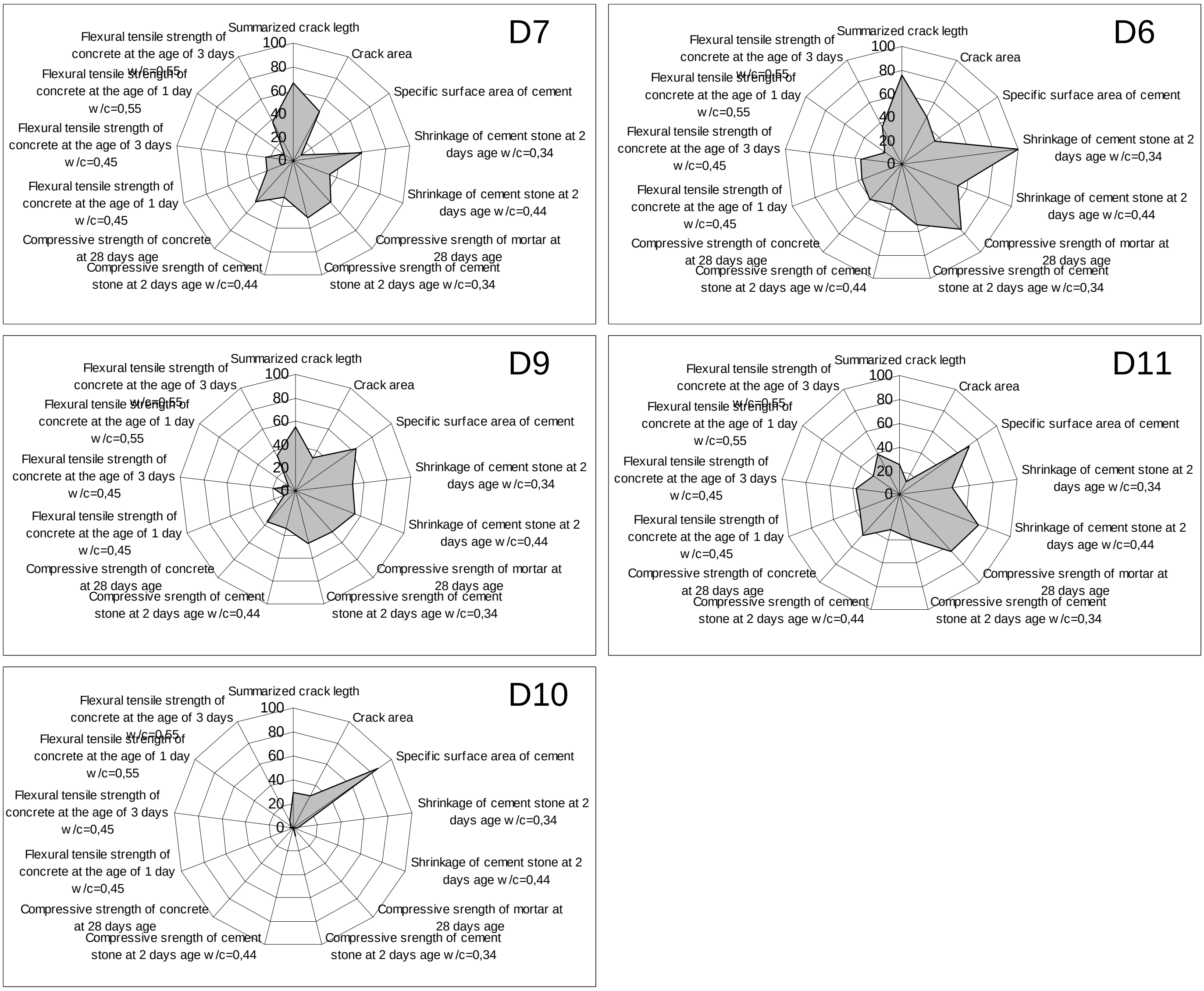


Fig. T13. Relationships between CEM II cement type, and crack length and crack area sorted by the early age shrinkage cracking tendency

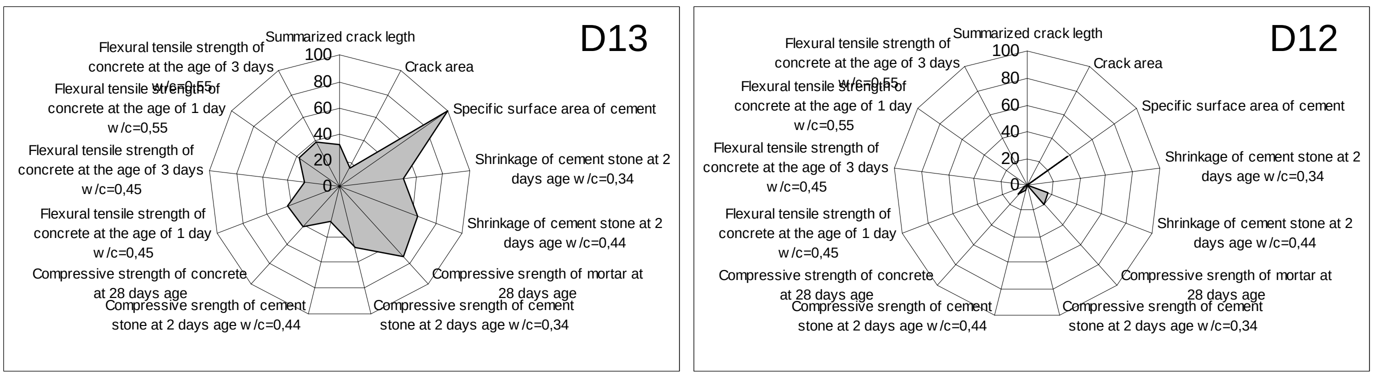


Fig. T14. Relationships between CEM III cement type, and crack length and crack area sorted by the early age shrinkage cracking tendency

4.3.5.

I have experimentally shown that there is a relationship between the early age shrinkage cracking tendency of the tested concretes and the type of the used cement. In case of blended cement types, increasing slag or fly ash content decreases the early age shrinkage cracking tendency. (*Fig. T15-19.*). It can be seen, that cements with high hydraulic additive content are advantageous to prevent early age shrinkage cracking tendency of concretes.

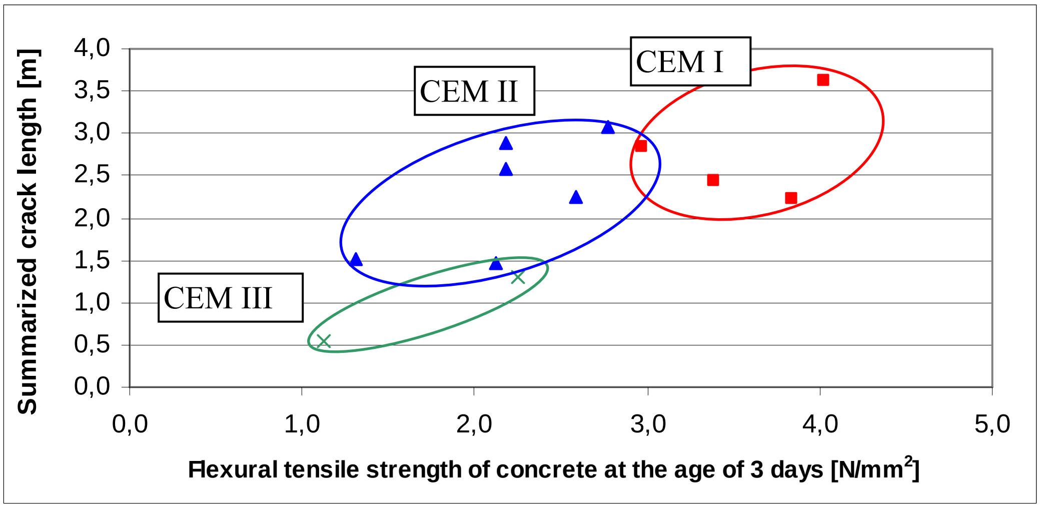


Fig. T15. Relationship between early age shrinkage cracking tendency of concrete rings (average of four specimens) and the flexural tensile strength of concrete prisms at the age of 3 days (average of three specimens, w/c = 0.55) using different cement types

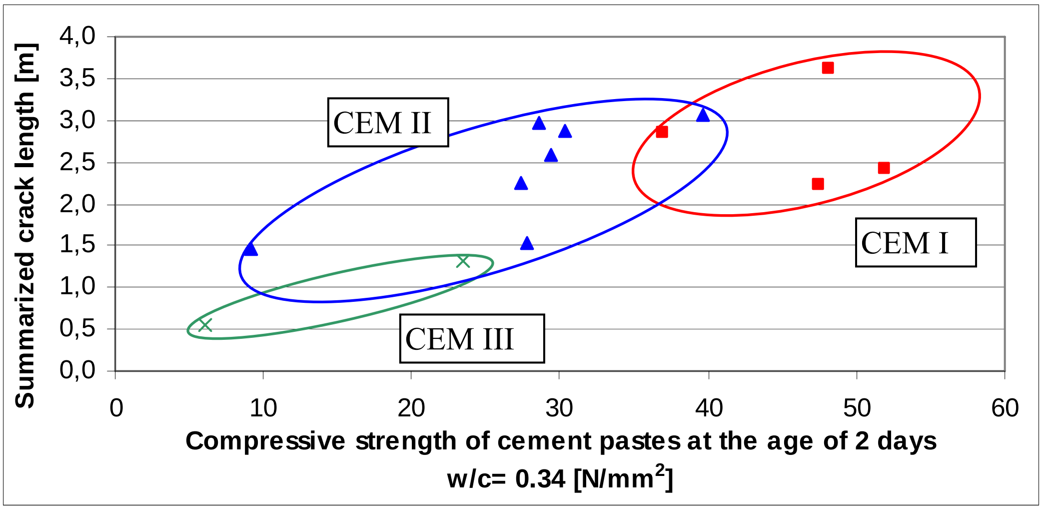


Fig. T16. Relationship between early age shrinkage cracking tendency of concrete rings (average of four specimens) and the compressive strength of the cement paste prisms at the age of 2 days (average of three specimens, w/c = 0.34) using different cement types

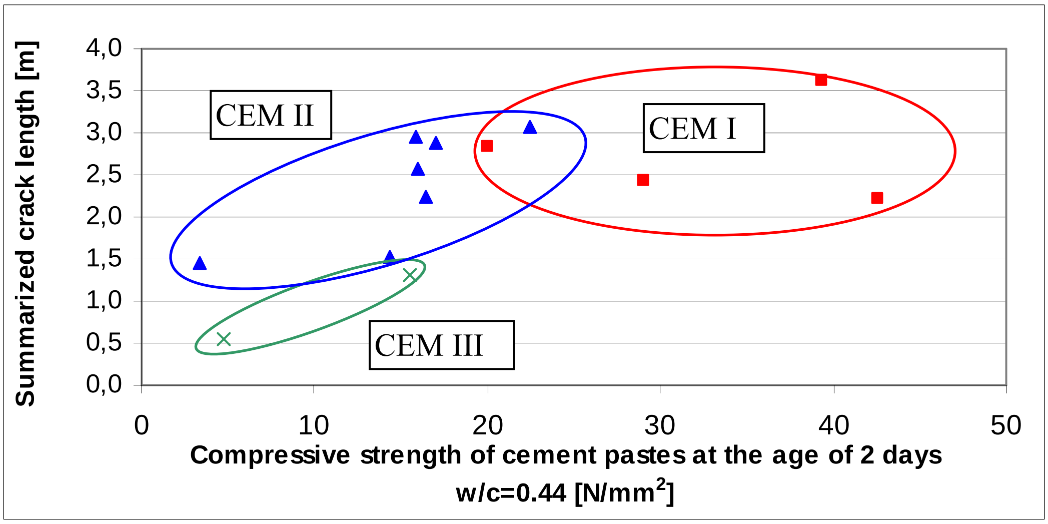


Fig. T17. Relationship between early age shrinkage cracking tendency of concrete rings (average of four specimens) and the compressive strength of the cement paste prisms at the age of 2 days (average of three specimens, w/c = 0.44) using different cement types

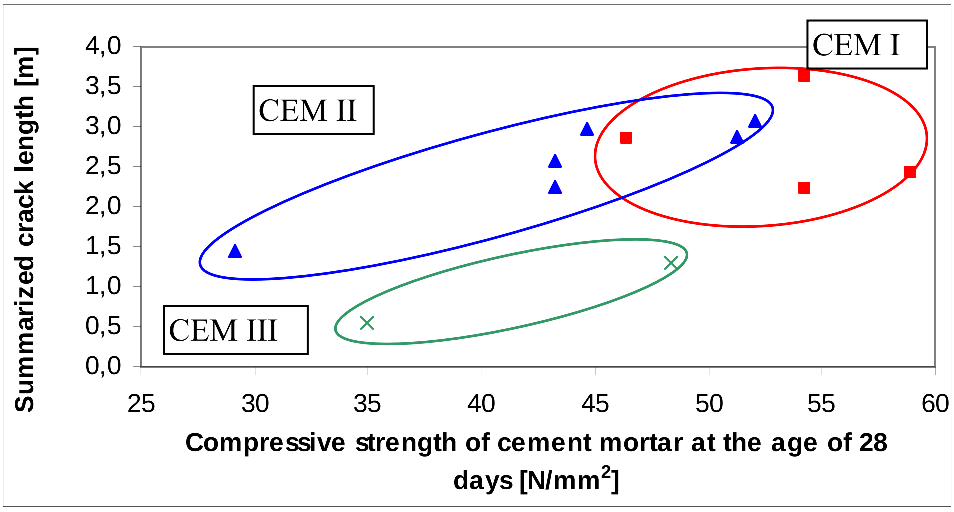


Fig. T18. Relationship between early age shrinkage cracking tendency of concrete rings (average of four specimens) and the compressive strength of the cement mortar prisms at the age of 28 days (average of three specimens, w/c = 0.50) using different cement types

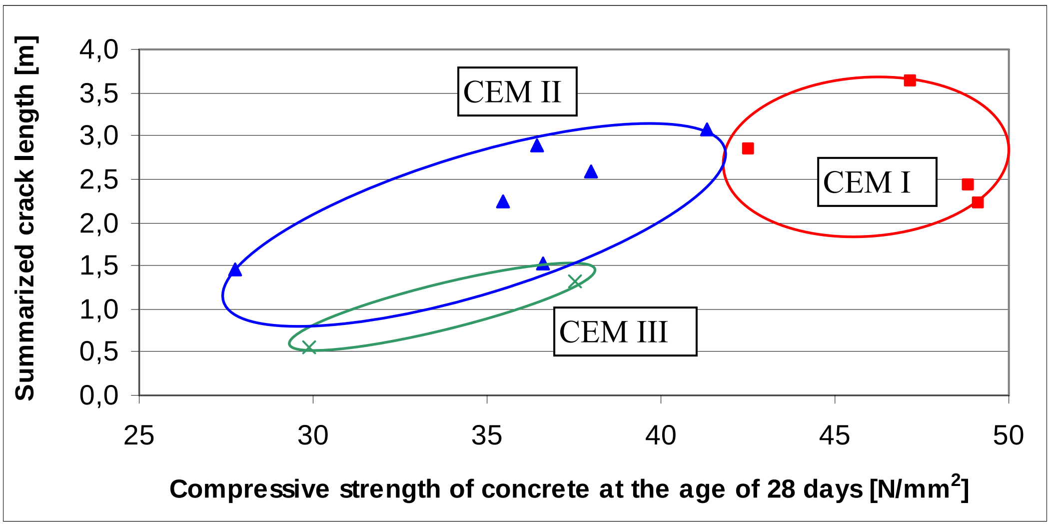


Fig. T19. Relationship between early age shrinkage cracking tendency of concretes (average of four specimens) and the compressive strength of concrete cubes at the age of 28 days (average of three specimens, w/c = 0.61) using different cement types

5. APPLICATION POSSIBILITIES OF THE NEW SCIENTIFIC RESULTS

The presented new scientific results can help to reduce early age shrinkage cracking tendency and the amount of cracks on concrete and reinforced concrete structures. Crack formation significantly influence durability of concrete. Engineers should know the causes of crack formation, and to reduce their affects. This requirement has high importance for example during building reconstructions applying LWAC (that can be advantageous for concrete slabs due to their lower dead load). Reconstruction layers are mostly thin concrete plates therefore cracking tendency is a very important property, it is essential to reduce it. Based on my new scientific results it is easy to predict the influence on the early age shrinkage cracking tendency of ***LWAC*** based on the water absorption of lightweight aggregate and choose the optimal ***lightweight aggregate type***.

According to the new scientific results it is easier to determine optimal fibre dosage in case of ***FRCs***. Using the applied test method it is easy to compare the crack reducing effectiveness of different fibre types. Based on the fibre geometry and material their crack reducing effectiveness can be predicted, which supports manufacturers and contractors choosing the optimal fibre type and effective dosage.

During concrete mix design the applied ***cement type*** is a determining parameter, which depends on many environmental parameters (weather conditions, temperature, applied technologies, strength, deformations, etc.). Based on the new scientific results it is easier to choose the optimal cement type for normal concretes from the point of view of early age shrinkage cracking tendency.

The new scientific results contain useful information in the fields of research and application too. In the future similar relationships can determined for other lightweight aggregates, fibres or cement types and the thesis can be adapted with certain constraints on new fibre and lightweight aggregate types too. Further future research fields are: investigation of the early age shrinkage cracking tendency of pure Portland cements made from the same clinker with different specific surface area, and the influence of hydraulic additive type and content of blended cements made from the same clinker.

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