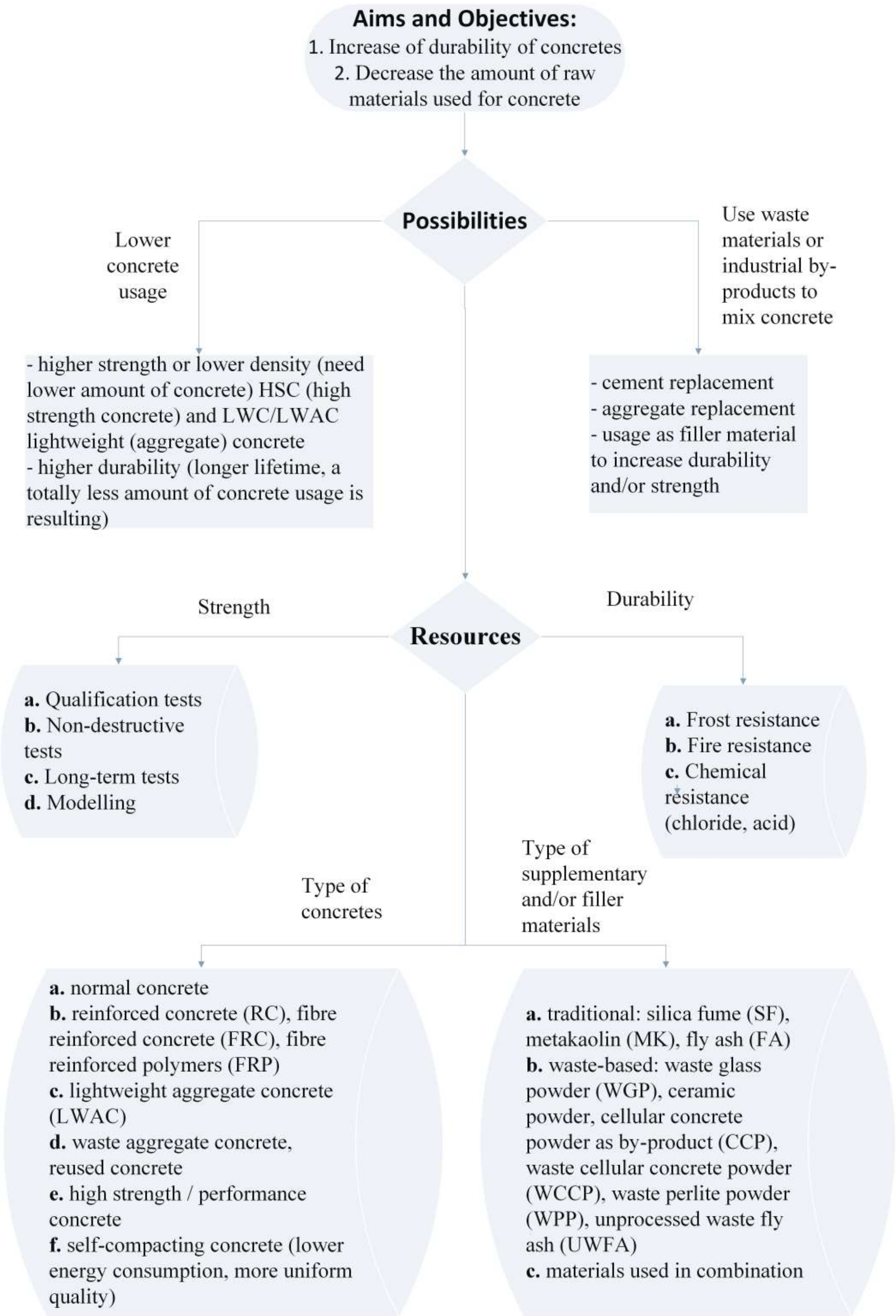
Final Report

OTKA K109233

Durability and performance characteristics of concretes with novel type supplementary materials



Test results and evaluation

All of the developed concrete mixtures have been tested for compressive and flexural-tensile strength. We have solved the preparation of high-strength concrete with normal and different types of waste aggregates and traditional or waste supplementary materials. These have been combined with each other and with other wastes in concrete. Due to subsequent quality control and condition control we also tested the effect of waste materials on non-destructive tests. It was also investigated that how can we consider the effect of these waste aggregates and supplementary materials in numerical models.

<u>Effect of supplementary materials</u>

Supplementary cementitious materials (SCMs) contribute to the hydration of Portland cement by physical phenomena (e.g. nucleation effect) or by chemical reactions (e.g. pozzolanic activity). Due to the pozzolanic activity and the filling effect, use of SCMs can result high performance concrete having both enhanced mechanical characteristics and reduced permeability that leads to improved durability. One of the aims was to reveal if there is any advantage of the combined use of traditional SCMs (silica fume and metakaolin), effect of waste powder materials (glass, perlite, fly ash, CCP) and combined use of traditional and waste SCMs. The evaluation of these effects is time-consuming and have been subject for 600 days. We have made our findings on traditional SCMs. The waste SCM and filler material was tested until 270 days.

<u>The traditional SCMs, metakaolin (MK) and silica fume (SF)</u> were tested in strong chemical environment (acid and chloride solution) independently and combined in different dosage. The tests were continued for 390 days.

The acid resistance of the concrete was tested in sulphuric acid environment.. In addition to sulphuric acid (pH=1), the effect of an organic acid was also tested. The acetic acid (pH=3) partly dissociates in water and reacts both with hydrated and anhydrated compounds of cement paste to form mainly calcium salts. Calcium-acetate is formed, which is very soluble. In acetic acid a considerable loss of mass as well as change in volume was recognized for every tested specimens of each mixture.

After 390 days, the sulphuric acid caused 9% weight loss on pure cement paste samples. The introduction of SF in the mixture decreased the weight loss to 3-4 %, but a more prominent result was produced by the usage of 10 % MK, which decreased the change of mass to 0.5 %.

In case of acetic acid, the mass change was extremely high, about 50%, which has improved by 10%, if MK was introduced in the mixture. The other applied SCMs were ineffective.

The value of chloride migration was reduced at least by 40% in case of all applied SCMs, the most outstanding was the action of SF with its 70% migration reducing effect.

Several <u>waste-based supplementary materials</u> were compared to traditional ones: waste glass powder (WGP), ceramic powder, cellular concrete powder (WCCP), waste perlite powder (WPP), unprocessed waste fly ash (UWFA).

Cement was substituted with WGP at levels of 20% or 30% per mass. It was demonstrated that the WGP addition improves the workability of fresh pastes, but it decreased the strength. It was also demonstrated that the particle size of WGP (due to its high specific surface area) has a stronger influence on the effectiveness on the cement replacement than the chemical composition. The effectiveness of the cement replacement increases as the specific surface area increases. We also sought other materials with different grain sizes that work well without processing. Grinding is possible, but it is also energy-consuming and expensive. We measured this for other silicate waste as well.

The aim of this feasibility study was to find alternative materials, which can be used as an SCM, they are actual waste materials, because the traditionally used SCMs (that were originally made of industrial waste) turned into industrial products with relatively high production cost. The materials were tested for compressive strength and durability.

Construction waste materials were received from industrial partners and applied as supplementary materials. 10% by mass (relative to the cement amount) of CCP or clay brick powder were used in the mixes, which were compared with a reference mix (without any SCM) and with a mix that contained air-entraining agent. The application of air-entraining agent in concrete is frequently recommended to increase the durability of concrete. Standard cubes with 150 mm of edge length were cast, and after 28 days compressive strength tests were carried. The durability of the concrete was investigated with two different methods. First the cubes were subjected to 50, 100 and 150 cycles of freezing and thawing effect, then the mass and strength loss of the samples were measured. Besides that, the freeze-thaw scaling resistance of the specimens was investigated by applying 7, 14, 21 up to 56 cycles of freeze-thaw scaling. All the applied methods were carried out in compliance with the recommendations of the CEN/TS 12390- 9:2007 standard. It was tested on the most commonly used normal strength concrete (C25/30).

Based on the results of the tests it can be concluded that air-entraining agent highly improved the frost resistance of concrete as it was expected, although it significantly decreased the compressive strength (30%) of the material and its cost is high if compared to the other investigated solutions. The clay brick powder has no significant effect on the strength of concrete or on its durability, but is a good possibility for waste recycling. The CCP is able to increase the compressive strength significantly (by 37%) and it has a positive effect on the durability performance of the concrete as well. Based on the freeze-thaw test, the concrete with CCP lost less than 5% of its compressive strength after 150 cycles.

Due to the favorable results with CCP, further investigations were carried out with several different dosages (3, 10 and 17%) as cement substitution. The results were compared with a mix that contained only metakaolin (MK10%) as SCM and with a mix, where the CCP was combined with MK (MK/CCP in 7/3%). Based on the results, it can be seen that a given amount of CCP can increase the strength and durability of concrete as well (~10%), however too much of it can cause detrimental effects, especially in compressive strength (~17%). It was also shown, that the correct amount of CCP can have a better performance, than the metakaolin has on the durability of concrete, despite that metakaolin increases the compressive strength more, than the CCP. However, it is also important to see that CCP is completely a waste material without any need of production and preparation, which means a significant decrease in cost and in CO_2 emission as well. The results indicates that the combination of the two investigated supplementary material can be advantageous for many applications. The combined mix performed well on the durability tests and it increased significantly the compressive strength as well. It was not as advantageous in the freeze-thaw test as the mix with 3% of CCP and it did not increased the compressive strength much as the 10% of metakaolin, however it had the best performance on the frost resistance tests. Lastly, it can be concluded that the correct amount of CCP or the combination of CCP and metakaolin can increase both the strength and the durability of normal concrete, without highly influencing the cost of the material.

Combined use of metakaolin and silica fume or cellular concrete powder did not result in better performance in compressive strength than the separate use of SCMs in aspect of strength and durability, too.

Fire resistance is an increasingly important design principle. In the case of concrete, the raw materials and porosity have the greatest effect in addition to the actual moisture content. In our research we changed the type of aggregate (e.g. recycled concrete) and applied new type of SCMs.

In this research program the impact of incorporating recycled aggregate (RA) and different pure waste powder materials on the residual mechanical properties of concrete at elevated temperatures was tested. The used waste powder materials in the present study are unprocessed waste fly ash (UWFA), waste cellular concrete powder (WCCP), and waste perlite powder (WPP), where they proved their ability to enhance the behavior of concrete at elevated temperature when they replaced the cement up to 15%. However their effectiveness decrease in case of recycled aggregate concrete (RAC). Using RA up to 50% enhance the residual mechanical properties of concrete at elevated temperature due to the strong contact zone between two mortars as well as the similarity of thermal expansion between both of them.

Twenty-one mixtures of self-compacting high-strength concrete (SCHSC) incorporating recycled concrete aggregate (RCA) and pure waste powder materials have been long-time tested (till age of 270 days) for residual compression and flexural strength after exposure to fire. The results were compared to the results of the same concrete types and tests, which have been done at age of 90 days. A new parameter is introduced for comparism between the responses of concrete for the elevated temperature at different ages. This parameter is the "heat resistance" which expresses the total area under the curve of the relative residual compression or flexural strength (20 to 800 ◦C). The results show that the age of concrete has an influence on the response of concrete after elevated temperature. The heat resistance of compression strength enhances with age with differences in the tendencies at different temperatures. The heat resistance of flexural strength decreased by the maximum of 10%. The main reason for the change in the behavior is the water content and the degree of hydration of the binder. Using RCA gave better performance at high-temperatures. The used waste powder materials were unprocessed waste fly ash (UWFA), waste cellular concrete powder (WCCP) and waste perlite powder (WPP) where using any of them up to 15% instead of cement with 0% or 25% of RCA enhance the concrete resistance against heat at long ages. However, long ages testing properties of concrete simulate the real behavior of concrete structures accurately.

Special questions:

Reinforced concrete (RC), fibre reinforced concrete (FRC), fibre reinforced polymers (FRP)

It was tested whether the used SCMs had any negative effect on any form of reinforcement, but we did not experience any unfavorable behavior. Changing the reinforcement to the mechanical properties is much more effective than durability. Thus, the investigations were not conducted in further details.

Lightweight aggregate concrete (LWAC)

Decreasing self weight reduces the needed amount of material. Strength is designable, but durability problems are always encountered when using porous aggregates.

Durability of lightweight aggregate concrete with different groups of aggregate (typically with different water absorption capacities) were tested in terms of freeze-thaw resistance up to 150 freeze-thaw cycles. Open pore lightweight aggregates and closed pore lightweight aggregate have been used for the comparison to normal weight concretes. It was revealed that the tendency and magnitude of deterioration for the high strength samples, open pore expanded clay aggregates is similar to that of the normal weight aggregates. The very light, low strength, open pore lightweight aggregates (both expanded clay and expanded glass) showed special behaviour; the minimum strength does not correspond to the maximum freeze-thaw cycle that needs further experimental studies for a more complete understanding. The closed pore expanded glass aggregates show slight increase in compressive strength up to 25-50 cycles, however, between 100-150 cycles resulted complete failure, a more serious deterioration than what was found for the other types of lightweight aggregates.

Waste aggregate concrete (crushed concrete and crushed aerated concrete)

Cellular concrete (CC) blocks cannot be reused in the form of building blocks as traditional clay bricks. The typical form of CC waste is crushed stone or powder. In this research program is dealing with the possibilities of the recycling of CC waste as concrete aggregate, prefabricated concrete tiles, concrete blocks, shuttering blocks and cement supplementary material. The concrete mixes were designed in a way to apply as much CC waste as possible and to require the least further processing of the waste material at the same time. Mechanical, thermal and durability properties of the samples containing CC waste as aggregate or supplementary material were tested. The results indicated that opportunities in applying aerated concrete waste in granular form as aggregate for load bearing purposes are limited, but in powdered form can be highly advantageous if the particle size is lower, than 0,09 mm.

High strength / high performance concrete

We achieved compressive strength above 80 MPa (C55/67) and frost resistance to the most stringent class of Hungarian Standard, including reused aggregate concrete and waste powders.

Self-compacting concrete

We have successfully produced SCC with waste powder filler materials, for both high strength and recycled aggregate concrete. This reduced the amount of needed production energy and stabilized the quality, which is important both from the point of view of strength and durability.

Different non-destructive test possibilities was checked.

The most popularly used non-destructive testing (rebound hammer and ultrasonic method) of concrete was also completed in different ages (from 3 to 360 days). In case of the rebound hammer test it is known from earlier researches, that the same rebound values belong to lower LWAC compressive strengths then that of NWC. From the results however the conclusion can be drawn, that the type of raw material, out of which lightweight aggregate is produced, has also a significant influence on the results between 10 to 25%). In case of higher strength classes this difference is less significant. When the tests are carried out by ultrasonic method, differences can also be detected in the strength of NWC and LWAC. Having the same ultrasound velocities lower strength belongs to LWAC, but the deviation due to different LWA material can not be clearly observed. At the same time the moisture content of the material is of great importance. The results of the 90 days and 360 days measurements can be compared to each other. The results of the measurements on the 28 days old or younger concretes should be separately handled from the measurements done on the 90 days old or older concrete samples. Separately, in both cases the strength development can be followed well.

We have investigated the effect of new materials on the settings of the numerical models.

In first step the discrete element models of concrete specimens were completed in various sizes and shapes and tested for compressive strength to define relations and later to be able using the smaller samples for the determination of the compressive strength. The tests were done for concretes from different strength classes.

Based on the data evaluation of numerical model results it can be confirmed that the Discrete Element Method (DEM) model was able to sufficiently describe the compressive strengths test on different types of specimens and the hardness testing method. With the help of these models the laboratory test procedures can be simulated in a large scale, without using real specimens. As a conclusion it can be stated that the DEM is a useful method for the simulation of Brinell hardness testing of hardened concrete.

The results is the description of the relationship between the normal strength of the parallel bonds (σ_{pb}) (DEM model variable) and the density (ρ) and compressive strength (σ_{comp}) of the real material. Using the above described model, the parameters were optimized.

Article under publication (under review)

Mohammed Abed, Rita Nemes, Éva Lublóy T**he Impact of Age on the Fire resistance of Recycled Aggregate Concrete**, Advances in Civil Engineering, ISSN: 1687-8094

Mohammed Abed, Rita Nemes **Mechanical Properties of Recycled Aggregate Self-Compacting Concrete Utilizing Waste Fly Ash and Perlite Powder**, Periodica Polytechnica Civil Engineering, ISSN 2064-4477