Ceramics-Silikáty 66 (4), 520-526 (2022)
www.ceramics-silikaty.cz doi: 10.13168/cs.2022.0048

THE EFFECT OF CRUSHED GLASS AND METAKAOLIN WASTE IN THE PROPERTIES OF MODIFIED CONCRETE

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Submitted September 2, 2022; accepted October 5, 2022

Keywords: Metakaolin waste; Crushed waste glass; Density; Porosity

This paper examines the possibility of using waste crushed glass as a substitute for sand, and waste from the production of foaming agent - metakaolin as a substitute for cement in the production of modified concrete. Concrete mixes were formulated with different amounts of metakaolin (M) replacing cement at 5 %, 10 %, 15 % and 20 % and 25 % crushed glass (TS) replacing sand. From the results of the research, it can be said that crushed glass waste and metakaolin waste can be used in the production of modified concrete, while reducing the amount of cement and sand. The optimal amounts of waste to replace part of cement and sand is 10 % of metakaolin waste and 25 % of crushed glass waste, with which concrete mix increase density, ultrasonic pulse velocity (UPV), compressive strength, frost resistance cycles, absorption decreases. Thus, using metakaolin waste 10 % (replacing Portland cement) and 25 % crushed glass waste (replacing sand) in concrete mixes results in more durability concrete can be used in building structures.

INTRODUCTION

Various admixtures and additives are used in the preparation of concrete mixes to control the technological properties of the mix as well as physical and mechanical properties of hardened concrete. The research into the effects of these additives on the physical and mechanical properties of concrete is important for the effective use of the additives and to achieve the required properties of hardened concrete.

Fast development of new materials and emerging material technologies demand for cement-based building materials and concrete with better performance characteristics. Industrial waste, such as crushed waste glass, metakaolin, etc. can be used to improve the essential properties of concrete. The use of waste in the production of modified concrete reduces CO_2 emission from cement production and lower construction costs due to the reduced price of concrete. Portland cement manufacturing causes very high CO_2 emissions accounting for around 7 % of the total global CO_2 emission per annum [1].

The concrete industry currently faces major challenges in finding cost-effective strategies to reduce carbon dioxide emissions from Portland cement manufacture. The construction industry is one of the world's biggest CO_2 emitters, accounting for up to 8 % of the global cement production related CO_2 emissions, whereas the natural resources are depleted by using sand for the production of mortar and concrete [2-3].

One of the most common environmental impact abatement techniques in concrete industry is the replacement of cement and natural aggregates with mineral materials reclaimed from industrial waste [4-10].

Different alternatives, such as crushed glass, glass powder and metakaolin are considered to be viable solutions for a greener and more sustainable civil construction industry as these secondary raw materials are readily available [11-13].

There are two ways to use waste glass in concrete production. It can replace a certain part of the fine aggregate or can be used as a cement substitute. The use of waste glass to make recycled aggregates for concrete reduces the depletion of natural resources and the area taken by landfills. The strength of concrete increases when part of cement is replaced by metakaolin and part of sand is replaced by crushed glass [14-15].

Researchers found that the compressive strength of the specimens modified with 10 % of plastic and crushed waste glass was higher than the strength of control specimens. The compressive strength of concrete also increased when the aggregates were substituted by waste glass together with slag [16-17].

Researchers found that 20 % of cement can be replaced by 20 mm-size waste glass without any negative effect on mechanical properties of concrete. The mechanical properties deteriorate in proportion to the increase of waste glass content. The compressive strength of concrete increases by 2.5 MPa when 15 % of sand in concrete mix is replaced by crushed glass [3, 18].

Metakaolin, when added to concrete mix, causes a pozzolanic reaction that improves the microstructure of the cement paste. Compared to ordinary Portland cement, the reaction is faster due to a small particle size and big surface area of metakaolin. The amount of metakaolin ranges between 5 % and 10 %. The pozzolanic properties make metakaolin a good additive in Portland cement concrete manufacture. The density of concrete reduces with higher metakaolin content. The biggest drop in density was observed when 30 % of Portland cement was replaced by metakaolin [19-21].

Researchers claim that the greatest effect is achieved with 10 % of metakaolin added. With this content of metakaolin in the mix the compressive strength of concrete increases up to 10 %, the flexural strength increases up to 50 %, and the porosity reduces 35 %. Higher than 30 % content of metakaolin increases the porosity and reduces the strength of hardened concrete due to the higher water and binder ratio (W/B) [22-23].

Other researchers also studied the effect of metakaolin content on the properties of concrete. A constant W/B ratio and three different contents of metakaolin added at 5 %, 10 % and 15 % by weight of cement were used in high performance concrete tests. According to the tests results, the optimal amount of metakaolin is 10 %. Such an amount of metakaolin produced a 5 % increase in the compressive strength and 8 % increase in the splitting strength of concrete. Li and Ding obtained similar results. They obtained the highest compressive strength by adding 10 % of metakaolin. Researchers found that metakaolin not only increased the strength properties of concrete but also reduced the capillary absorption of water and chlorides by 77 % and 80 % respectively. It also reduced the total water absorption of concrete by 30 %. The decrease in absorption is caused by metakaolin particles that distribute evenly among the concrete particles and thus reduce the porosity of concrete, subsequently the capillary and total water absorption [24-25].

Water absorption decreases in concrete modified with metakaolin. Metakaolin added to concrete increases compressive strength, frost resistance, reduces drying shrinkage. Metakaolin particles fill in the pores or cracks and thus reduce the porosity of concrete. When part of concrete is replaced by metakaolin, water absorption of concrete decreases both after 28 and after 56 days of curing compared to unmodified concrete [26-28].

The compressive strength of concrete specimens where cement is replaced by up to 20 % of metakaolin was higher than the strength of control specimens, whereas the substitution of cement by 25 % of metakaolin caused the compressive strength of the test specimens to decrease [29].

Researchers concluded that metakaolin can increase the early strength and the elasticity modulus of concrete. The best improvement of mechanical properties at the early setting time was observed with the addition of 20 % of metakaolin [30].

Metakaolin, which is a by-product generated in foam glass production, and crushed glass have not been widely researched and have never been used together as cement and sand substitutes in the production of concrete.

EXPERIMENTAL

Portland cement CEM I R 42.5 complying with EN 197-1:2011, produced by JSC Akmenės Cementas was used in the investigation. Clinker mineral composition was: C_3S – 61.0 %, C_2S – 13.5 %, C_3A – 8.5 %, C_4AF – 10.5 %, SO_3 – 3.10 %, LOI – 1.43 %. Particle density is 3.11 g cm^{-3} and bulk density is 1.22 g cm^{-3}. Metakaolin characteristic provided in Table 1. Mineral composition is provided in Table 2. Crushed glass characteristic: particle density - 2294 $kg \cdot m^{-3}$; bulk density - 1204 $kg \cdot m^{-3}$. 0/4 fraction sand complying with LST EN 12620:2003 requirements was used as a fine aggregate. 4/16 fraction gravel complying with standard LST EN 12620:2003 requirements was used as a coarse aggregate.

Table 1. Characteristic of metakaolin.

Properties	Metakaolin
Particle density ($kg \cdot m^{-3)}$)	2049
Bulk density ($kg \cdot m^{-3)}$)	421

The pozzolanic activity of metakaolin (927 $mg \cdot g^{-1}$). The analysis of metakaolin particle size distribution showed that 90 % of the particles were smaller than 75.79 µm, 50 % of metakaolin particles were smaller than 5.88 µm, and 10 % were smaller than 1.27 µm.

Mixing proportion of concrete for 1 m^3 provided in Table 3. Part of cement in the test specimens was replaced by metakaolin, the content of which ranged from 0 % to 20 %, whereas 25 % of sand was replaced by crushed glass, W/C – 0.49. Concrete mixes were made in the laboratory while forming the specimens in 100 × 100 × 100 mm metal forms. After 24 hours

Table 2. Mineral composition of metakaolin.

SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	SO_3	Na_2O	TiO_2	MgO	Other
50.6	34.0	0.74	2.49	0.7	0.07	10.1	0.37	0.59	0.34

Table 3. Mixing proportion of concrete for 1 m³.

Batches	Cement (kg)	Sand (kg)	Crushed glass (kg)	Crushed glass (%)	Gravel (kg)	Chemical admixtures	Metakaolin (kg)	Metakaolin (%)	Water (kg)	Slump class
M0+TS0	355	753	0	0	984	1.78	0	0	174	S3
M0+TS25	355	564.75	188.25	25	984	1.78	0	0	174	S3
M5+TS25	337.25	564.75	188.25	25	984	1.78	17.75	5	174	S3
M10+TS25	319.50	564.75	188.25	25	984	1.78	35.50	10	174	S3
M15+TS25	301.75	564.75	188.25	25	984	1.78	53.25	15	174	S3
M20+TS25	284.00	564.75	188.25	25	984	1.78	71.0	20	174	S3

the specimens were taken out from the forms and kept in water of 20 ± 2 °C for 28 days. The compressive strength of concrete cubes was tested according to EN 12390-2:2019 standard after 28 days and 90 day of curing in water [31].

EXO temperatures in concrete were measured using the methodology developed by Alcoa Company. A paste specimen of 1.5 kg weight was placed in a textolite moulder (10 × 10 × 10), according to LST EN 12390-15 [32].

The density of the specimens was measured according to EN 12390-7:2009 standard [33]. Ultrasonic pulse velocity was measured according to EN 12504-4:2004 standard [34]. Water absorbtion was measured after 4 days of soaking using the methods described in scientific to LST EN 13369:2018 standart [35]. Compressive strength concrete mixes was measured according to LST EN 12390-3:2019 [36].

Freeze-thaw resistance of concrete depends both on open porosity (the amount of capillary pores), and on closed porosity (air content in the mixture), and quantitatively can be determined by the frost resistance coefficient K_F [37]. Knowing the value of frost resistance coefficient K_F, the freeze-thaw resistance of the conglomerate can be predicted according to the function of conglomerate freeze-thaw resistance and frost resistance coefficient K_F [38].

RESULTS AND DISCUSSION

Structure of crystallising admixture was tested by means of X-ray diffraction analysis. The results of X-ray diffraction analysis are presented in Figure 1.

The XRD image shows the quartz and kaolinite peaks of metakaolin are the most intensive. The predominating mineral in metakaolin (76 %) is kaolinite ($Al_2Si_2O_5(OH)_4$) K. Muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$) M_s is the second mineral making 12 % of metakaolin. Quartz (SiO_2) Q is the third mineral by content, representing 8.9 %. The fourth mineral is microcline ($KAlSi_3O_8$) M_c.

SEM images of metakaolin microstructure are presented in Figure 2. The image magnified 1500 times (a) shows a lot of plate-shaped kaolinite particles. The image magnified 5000 times (b) shows that metakaolin particles are made of many crystals of irregular shape distributed in different directions.

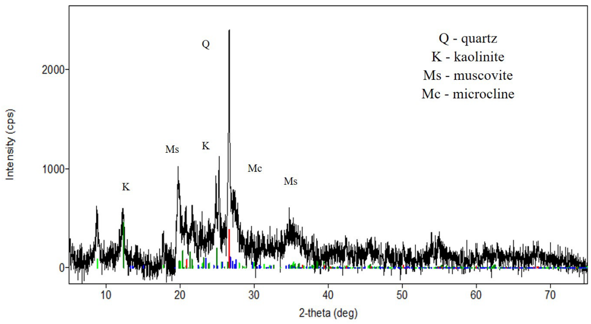
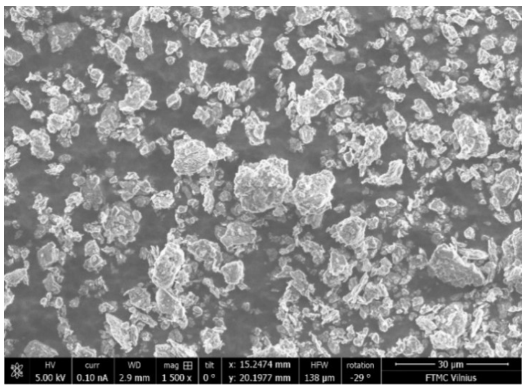
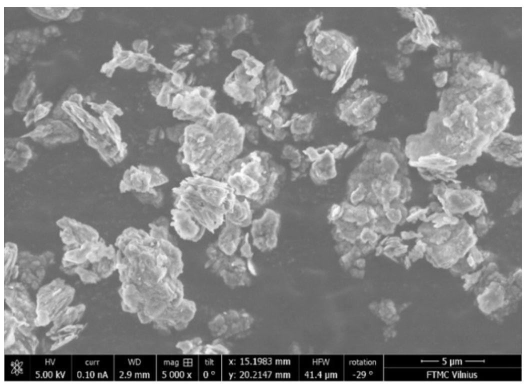


Figure 1. X-ray image of metakaolin.



a)



b)

Figure 2. The microstructure of metakaolin: a) x1500 magnification; b) x5000 magnification.

The heat of hydration (EXO) was measured for concrete mixes. Figure 3 illustrates the relationship between the content of substituting waste materials and the heat of hydration. The maximum temperature recorded for the control specimen was 28.82 °C with the temperature rise time of 18 h; the maximum temperature for the specimen modified with 25 % of crushed glass was 29.02 °C with the temperature rise time of 14 h; the maximum temperature for the specimen modified with 25 % of crushed glass and 5 % of metakaolin was 30.51 °C with the temperature rise time of 14 h; the maximum temperature for the specimen modified with 25 % of crushed glass and 10 % metakaolin was 30.74 °C with the temperature rise time of 14 h; the maximum temperature for the specimen modified with 25 % of crushed glass and 15 % metakaolin was 30.64 °C with the temperature rise time of 12 h; the maximum temperature for the specimen modified with 25 % of crushed glass and 20 % metakaolin was 30.19 °C with the temperature rise time of 12 h.

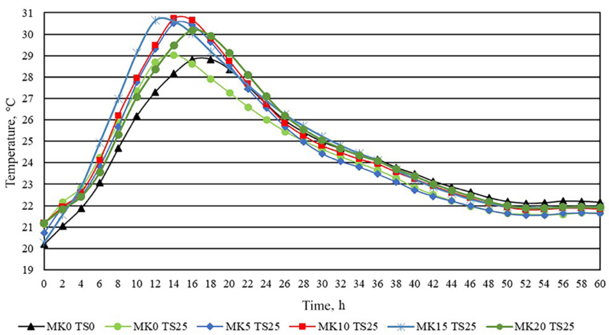


Figure 3. Hydration heat of concrete mixes.

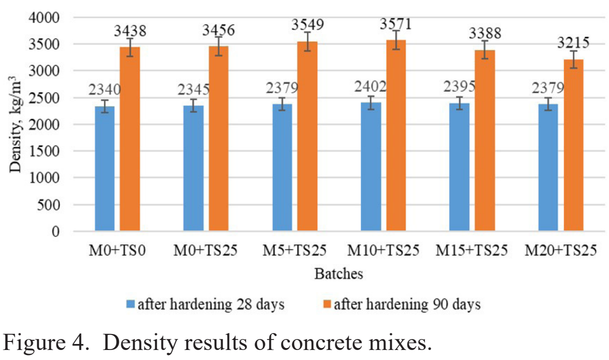


Figure 4. Density results of concrete mixes.

According to the test results of the specimens made with the same W/B ratio, the EXO temperature was the highest in the specimens where cement was replaced by 10 % of metakaolin and 25 % of sand was replaced by crushed glass. However, the maximum temperature goes down at a higher than 10 % content of metakaolin in the mix.

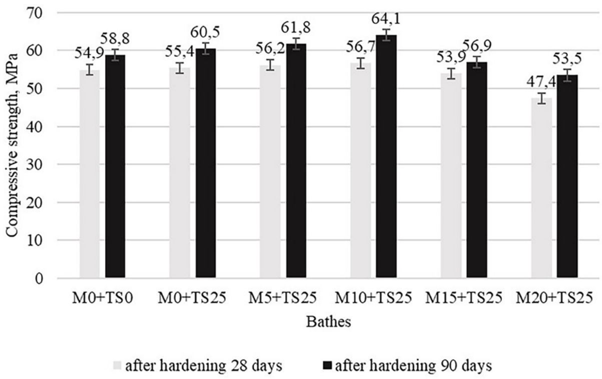


Figure 5. Compressive strength results of concrete mixes.

Density results showed that the density value of the specimens containing 25 % of crushed glass used as sand substitute slightly increased after 28 and 90 days of curing (Figure 4). The density also increased when part of cement was replaced by metakaolin (5 % and 10 %). When cement is replaced by 10 % of metakaolin, the density increases 3 % at 28 days and 4 % at 90 days. Such content of metakaolin is appropriate. However, the density value slightly reduces with a higher (15 % and 20 %) metakaolin content in the mix.

Figure 5 illustrates the results the compressive strength and the content of waste materials used in the mix. The results of compressive strength tests showed that the strength of the specimens where 25 % of sand was replaced by crushed glass slightly increased. The compressive strength also increased in the specimens modified with 5 % and 10 % of metakaolin. This amount of waste materials is appropriate to use in concrete mix. With a higher content (15 %) of metakaolin, the compressive strength slightly decreases, whereas a 20 % substitution of cement with metakaolin causes a significant drop of 14 % in compressive strength. The results of compressive strength tests at 90 days showed that the strength of the specimens where 25 % of sand was replaced by crushed glass increased 3 %. An 8 % increase in the compressive strength was recorded in the specimens containing 10 % of metakaolin. This amount of waste materials is appropriate to use instead of cement in concrete mix. 15 % and 20 % of metakaolin added into the mix cause the 3 % and 9 % drop in compressive strength respectively. As a result of the research, it was found that the compressive strength values of samples in which 10 % of cement was replaced by metakaolin and 25 % of sand by crushed glass increased.

UPV results with concrete samples cured for 28 and 90 days showed that at 28 days the UPV maximum value (4640 $m \cdot s^{-1}$) in the samples modified with 10 % of metakaolin (Figure 6). The UPV value in these specimens was 15 % higher than in the control specimens. Other amounts of metakaolin had almost no influence on UPV at 28 days. At 90 days the UPV value of 4884 $m\ s^{-1}$ was also the highest

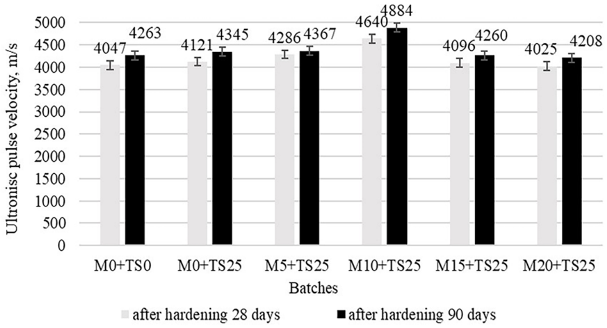


Figure 6. UPV results of concrete mixes.

in the specimens modified with 10 % of metakaolin. Compared to the control specimens, it was 14.5 % higher. Other amounts of metakaolin had almost no influence on UPV at 90 days. UPV value increased 5 % between 28 and 90 days of curing.

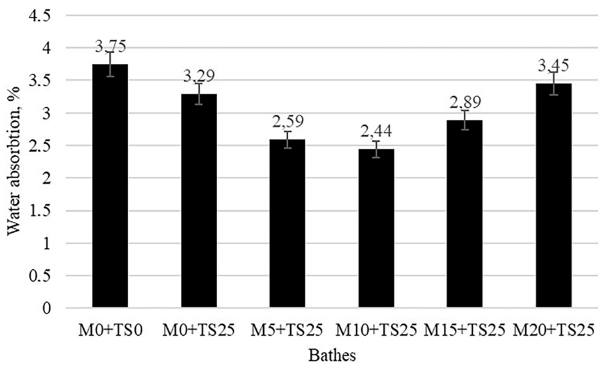


Figure 7. Water absorption results of concrete mixes.

Figure 7 illustrates the water absorption results of concrete specimens tested. The tests showed a slight decrease of water absorption in the specimens where 25 % of sand was replaced by crushed glass. A significant 35 % drop in water absorption was observed in the specimens where 5 % and 10 % of cement was replaced by metakaolin and 25 % of sand was replaced by crushed glass. The water absorption of concrete modified with crushed glass increases by increasing the content of metakaolin used as cement substitute up to 20 % but remains lower than the absorption of the control specimen.

Open, closed and total porosity of concrete specimens in which part of cement was replaced by metakaolin and part of sand was replaced by crushed glass was determined. The obtained results are presented in the Table 4. Closed porosity increased by replacing up to 10 % of cement with metakaolin. However, it started reducing with a higher content (15 % and 20 %) of metakaolin.

Table 4. Porosity results of concrete.

Batches	Open porosity (%)	Closed porosity (%)	Total porosity (%)
M0+TS0	8.52	3.45	11.97
M0+TS25	6.89	5.43	12.32
M5+TS25	6.74	6.74	12.60
M10+TS25	6.04	7.23	13.27
M15+TS25	6.54	6.73	13.46
M20+TS25	7.87	5.59	13.61

The highest total porosity of 8.52 % was recorded in the specimen where cement was replaced by 10 % of metakaolin and 25 % of sand was replaced by crushed glass.

The results frost resistance is presented in Figure 8. The results of freezing and thawing cycles showed that the sample where cement was changed by 10 % of metakaolin and 25 % of sand was replaced by crushed glass had the highest frost resistance and the unmodified control specimens had the lowest frost resistance. The predicted frost resistance based on the number of cycles in samples with crushed glass and metakaolin waste increased with increasing metakaolin content and reached 1210 cycles. The lowest number of cycles was obtained in the control samples and is 700 cycles. When comparing the control sample with the sample with the most waste, the predicted frost resistance by the number of cycles increased by 42 %. The reason for this difference is that the specimens in which the cement was replaced by metakaolin and the sand was replaced by crushed glass are frost resistant.

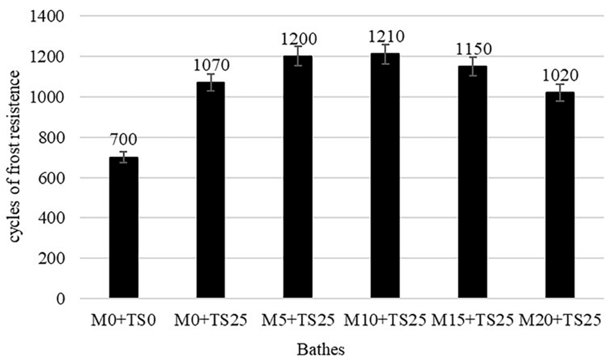


Figure 8. Results of frost resistance in the concrete mixes.

The results of the tests showed that metakaolin and crushed glass, used to substitute cement and sand in concrete mix, improve physical, mechanical properties of concrete mixes. The replacement of 10 % of cement by metakaolin and 25 % of sand by crushed glass caused water absorption and open porosity to decrease but the open porosity and frost resistance of the modified specimens increased and durability of the modified concrete mixes also improved.

CONCLUSIONS

The research showed that the highest density was achieved in concrete specimens modified with 10 % of metakaolin and 25 % of crushed glass. Ultrasonic pulse velocity values at 28 and 90 days were the highest, 4640 $m \cdot s^{-1}$ and 4884 $m \cdot s^{-1}$ respectively, in the specimens where 10 % of cement was replaced by metakaolin and 25 % of sand was replaced by crushed glass.

Waste metakaolin and crushed glass used to substitute 10 % of cement and 25 % of sand in concrete mix increase the compressive strength value at 28 and 90 days. The highest compressive strength value (56.7 MPa and 64.1 MPa) at 28 and 90 days respectively was recorded in the samples where 10 % of cement was replaced by metakaolin and 25 % of sand was replaced by crushed glass. At 28 and 90 days the compressive strength value of modified concrete was 2.3 % and 8.3 % bigger than the compressive strength value of control samples. The compressive strength value dropped to 53.9 MPa when more than 10 % of cement was replaced with metakaolin.

Concrete replacing 10 % of cement with metakaolin and 25 % of sand with ground glass was found to decrease water absorption and open porosity, but increase open porosity and frost resistance, and thus durability, of the modified specimens.

The results tests that crushed waste glass and metakaolin can be used to produce modified concrete. 35 % of waste materials utilised in the concrete mix make it possible to reduce the amount of cement and sand. Concrete modified with 10 % of cement and 25 % of crushed glass has better durability properties and frost resistance and can be used in construction industry.

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