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Basalt powder dependent properties of mortars subjected to high temperatures

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Research Paper

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Basalt powder dependent properties of mortars subjected to high temperatures

The effects of high temperatures of up to 800°C on residual physical and mechanical properties of mortars are presented in this paper. Due to its resistance to high temperatures, basalt powder is used as a substitute to standard sand at the ratios of 20% and 40%. Polypropylene or basalt fibres have been added to mortar mixtures to avoid spalling. Results show that the ratio of basalt powder does not change the strength reduction rate, and that the flexural strength performance of mortar mainly depends on fibre type and temperature rather than on basalt powder substitution.

Key words:
High temperature, fibre reinforcement, basalt powder, mechanical properties

Prethodno priopćenje

Veysel Akyuncu

Ponašanje morta s dodatkom bazaltnog praha pri visokim temperaturama

U radu je prikazan utjecaj temperatura do 800°C na rezidualna fizikalna i mehaničke svojstva morta. U istraživanju se kao zamjena za standardni pijesak koristi bazaltni prah u omjeru od 20 i 40 % zbog njegove otpornosti na visoke temperature. Mješavini morta didana su i polipropilenska ili bazaltna vlakna kako bi se izbjeglo odlamanje morta. Rezultati pokazuju da dodana količina bazaltnog praha ne utječe na smanjenje čvrstoće, te da savojna čvrstoća morta uglavnom ovisi o vrsti vlakana i temperaturi, a ne o primjeni zamjenskog bazaltnog praha.

Ključne riječi:
visoka temperatura, pojačanje vlaknima, bazaltni prah, mehanička svojstva

Vorherige Mitteilung

Veysel Akyuncu

Verhalten von Mörtel unter Zusatz von Basaltpulver bei hohen Temperaturen

Die Arbeit zeigt den Einfluss von Temperaturen bis zu 800 °C auf die restlichen physikalischen und mechanischen Eigenschaften des Mörtels. In der Studie wird Basaltpulver im Verhältnis von 20 zu 40 % aufgrund seiner hohen Temperaturbeständigkeit als Standard-Sandersatz verwendet. Didan-Mörtelmischungen sind auch Polypropylen- oder Basaltfasern, um Mörtelablagerungen zu vermeiden. Die Ergebnisse zeigen, dass die zugesetzte Menge an Basaltpulver die Festigkeitsreduzierung nicht beeinflusst und dass die Biegefestigkeit des Mörtels stark von der Art der Faser und der Temperatur abhängt und nicht von der Verwendung von Basaltersatzpulver.

Schlüsselwörter:
hohe Temperatur, Faserverstärkung, Basaltpulver, mechanische Eigenschaften

1. Introduction

The durability characteristics, such as resistance to fire induced high temperature, are important factors for the widespread acceptability of construction materials. The probability of fire incidents has greatly increased as residential buildings become more integrated, compact and constructed of composite material [1]. Portland cement is the most commonly used material in construction. It is known that Portland cement concrete performs very poorly at high temperatures [2, 3]. Portland cement starts to lose its compressive strength after exposure to critical temperature of approximately 600 °C [4]. Georgali and Tsaliridis [5] attribute this loss to the decomposed calcium hydroxide (CH) becoming calcium oxide, and to consequent volume expansion after cooling due to the rehydration of calcium oxide. Handoo et al. [6] concluded that the loss of crystalline water after 400 °C causes decomposition of product and subsequent mass loss. The interfacial bond between cement paste and aggregate weakens because of thermal incompatibility of these two concrete components. Also, explosive spalling occurs between the temperatures of 480 °C and 510 °C, which reduces the load bearing capacity of the concrete structure [7]. Although spalling phenomena is generally observed at high temperatures, lower temperatures of around 200 °C are also reported as spalling temperatures in [8, 9]. Heating rate, size and shape of samples, moisture content, permeability and strength of concrete can be regarded as factors that cause thermally induced spalling [10-12]. One of the most common methods to prevent spalling is the incorporation of polypropylene fibres, which increase the permeability of concrete at high temperatures and facilitate the evaporation of water. According to Akturk et al. [13] the spalling phenomena are effectively prevented when polypropylene fibre is used at 0.2 % of cement by weight.

Considering the objective of increasing the tensile strength of mortar at high temperatures, and reducing the level of mortar damage, the investigations made by the authors [14] show that steel fibres contribute to that objective.

The effect of aggregate type on concrete behaviour at elevated temperatures is of great importance and depends on mineralogical composition of the aggregate. At 570 °C, α-quartz (low temperature phase) transforms to β-quartz (high temperature phase) due to a polymorphic transformation in the siliceous aggregate. This leads to an increase in concrete volume and damage to concrete [15]. For the limestone and dolomite aggregate, carbonates alter to CaO or MgO at 800-900 °C [16]. The phase change is not observed for basalt aggregate at temperatures of up to 800 °C [17]. Hager et al. [18] assessed physical and mechanical properties of concrete containing various types of aggregates such as basalt, granite, dolomite, and riverbed gravel. The authors state that the aggregate type affects mechanical properties at temperatures of up to 400 °C. Beyond this temperature, the decomposition of portlandite is much more susceptible to strength reduction. In another research [19], it is reported that the concrete containing basalt aggregate has a lower thermal expansion coefficient than concrete containing calcareous aggregate, which results in better performance at high temperatures.

In this study, a basalt powder and a siliceous sand mixture are used to produce a mortar that performs better at high temperatures. The basalt powder is used in the mixture due to its durability at high temperatures. However, its fineness helps make the mortar denser due to its ability to fill small pores. In this case, PP fibres are added to the mixture to avoid the spalling phenomenon. For comparison, basalt fibres that can withstand high temperatures are added to a second mortar mixture instead of the PP fibres.

2. Experimental study

2.1. Materials and mixtures

Reference mortar (R) was prepared with CEM I 42.5 R, polycarboxylate based superplasticizer, and the standard RILEM Cembureau sand. Basalt powder (d_{50}≈30 μm) was replaced with sand by volume at the ratios of 20 % and 40 % and these mortar mixes were coded as B20 and B40 respectively. The particle densities of sand and basalt powder were found as 2.68 kg/m^3 and 2.73 kg/m^3 respectively. In addition, two different types of fibres were used at 0.5 % of mortar by volume, i.e. polypropylene fibre (PP) and basalt fibre (BF), to prepare fibre reinforced mortar mixes. The detailed properties of the fibres are given in Table 1. The mix codes of fibre reinforced mortars were attained according to the type of fibre used. For example, PP reinforced reference mortar group was coded as RF while BF reinforced reference mortar group was coded as RBF. The mix proportions and fresh properties of the mortar mixes are shown in Table 2.

2.2. Heating procedure and testing

After 28 days of curing in water, three specimens for each mixture and temperature were kept in oven at 105 °C for 24 h before heating. These specimens were then put into furnace and exposed to elevated temperatures of 300 °C, 600 °C and 800 °C for 2 h at the heating rate of 6-10 °C/min. After the heating procedure the specimens were taken out of the furnace and allowed to cool in air at room temperature.

Table 1. Properties of polypropylene and basalt fibres

Fibre type	Length [mm]	Diameter [μm]	Modulus of elasticity [GPa]	Elongation [%]	Tensile strength [MPa]	Density [g/cm^3]	Melting point [°C]
PP	6	--	3.5	25	350-700	0.91	160
BF	6	13-20	89	3.15	4100-4800	2.80	1280

Table 2. Mix proportions and fresh properties

Mixtures	Cement [kg/m³]	Water [kg/m³]	Sand [kg/m³]	Basalt powder [kg/m³]	Fibre content [%. po obujmu]	Superplasticizer [kg/m³]	Flow [cm]	Fresh density [kg/m³]
R	500	250	1500	--	--	--	17.0	2254
B20	500	250	1200	306	--	1.5	17.8	2233
B40	500	250	900	611	--	2.5	16.5	2328
RF	500	250	1500	--	0.5	5	17.2	2157
RBF	500	250	1500	--	0.5	5	16.7	2202
B20F	500	250	1200	306	0.5	6.5	17.0	2160
B20BF	500	250	1200	306	0.5	6.5	16.8	2203
B40F	500	250	900	611	0.5	7.5	16.5	2115
B40BF	500	250	900	611	0.5	7.5	15.0	2159

The volume of permeable pore space was determined according to ASTM C642 [20] on the portion of prismatic samples broken during the flexural strength test. Oven dried and weighed samples were immersed in water and boiled for 5h, after which the saturated mass of samples was determined. The pore space percentage was calculated using the following formula (1):

$$Pore\ space, \% = \frac{C-A}{C-D} x100 \qquad (1)$$

where A is the mass of oven-dried sample in air (g), C is the mass of surface-dry sample in air after immersion and boiling (g), and D is the apparent mass of sample in water after immersion and boiling (g).

The ultrasonic pulse velocity test was performed according to EN 12504-4 [21]. The test was conducted on three specimens measuring 40 x 40 x 160 mm for each mortar series.

The flexural and compressive strength of mortars was determined on 40 x 40 x 160 mm samples at 28 days as per EN 196-1 [22]. Mechanical tests were carried out on three samples for each temperature after the heating procedure to obtain residual strength. The fracture toughness of samples was determined on 40 x 40 x 160 mm beams by applying the three-point bending test. The test was carried out under deflection controlled mode and the effective span length was 100 mm. The mid-span deflection was measured with the video extensometer.

3. Results and discussion

3.1. Physical properties

Physical properties of mortars exposed to elevated temperatures were investigated in terms of porosity and ultrasonic pulse velocity (UPV). The change in porosity and UPV of mortars under the effect of high temperatures is shown in Figures 1-4.

The relative porosity of mortars was calculated as the percentage of porosity retained by mortar with respect to porosity of the reference mortar that was not exposed to high temperatures. As can be seen in Figures 1 and 2 the relative porosity gradually increased when the mortar was heated up to 800 °C regardless of the amount of basalt powder and the type of fibre. Replacement ratio up to 20 % of siliceous aggregate with basalt powder showed beneficial effects at all temperatures. The rise of porosity in B20 samples was found to be lower than the reference and B40 mortars and the difference became significantly larger at 800 °C. The porosity increment percentages of reference mortar were just over the B40 mortars for the temperatures between 300 °C and 800 °C. This means that the replacement ratio of 40 % of basalt powder did not notably affect the high temperature resistance of mortars up to 800 °C. This can be attributed to the contribution of basalt powder to the microstructure of mortars; a denser microstructure resulted in reduced water vapour migration. Thus, the reduced water vapour migration induced vapour pressure build up and consequently formation of cracks in the cement matrix. To overcome this phenomenon, an additional porosity and micro channels can be created by incorporation of PP fibres into the matrix system that melts at about 160-170 °C. Test results shown in Figure 2 can be seen as an evidence of this explanation. Mortars with 40 % basalt powder and PP fibres showed the best performance at all temperatures (Figure 2). B40 mixes have higher porosity increment than B20 without fibre addition. On the other hand, mortars with 40 % basalt powder exhibit lower porosity increment than B20 with the addition of PP fibres. For example, the porosity of B20 increased up to 156 % while B40 increased up to 192 % at 800 °C, but this trend has changed controversially with the incorporation of PP fibres at the same exposure temperature. The porosity of B40F increased by 192 % while that of B20BF increased by 211 %. In order to understand positive effect of fibres in B40 series, additional pores resulting from fibre melting should also be taken into account. The porosity of samples without fibre slightly increased but the samples with polypropylene fibres increased dramatically at the temperature of 300 °C which is above the melting point of the fibres.

The addition of BF changed the behaviour of mortars under high temperature effect. Although the rise in the porosity of mixes without basalt powder (R) remained just below the rest of the mixes (Figure 2), mortars incorporating basalt powder showed better performance with the addition of BF. At 300 °C, B20BF and B40BF samples were not affected significantly. Beyond this temperature, the porosity increased dramatically but the increment rates were lower than the reference mortars or those reinforced with PP fibres. The reason for such result might be due to the higher melting point of BF than the PP fibres.

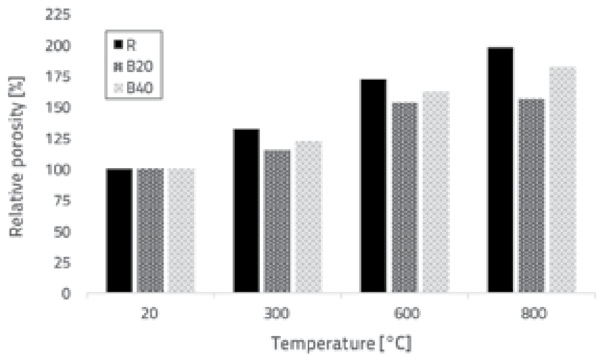

Figure 1. Relative porosity of reference mortars and mortars with basalt powder

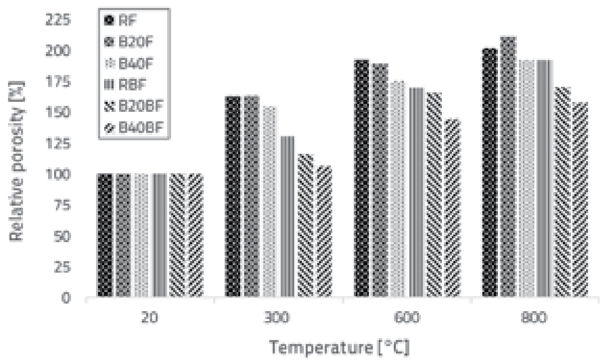

Figure 2. Relative porosity of fibre reinforced mortars

Ultrasound measurements were also performed for all series after exposure to elevated temperatures. Prior to ultrasonic pulse velocity measurements, the samples were allowed to cool to room temperature. Figures 3 and 4 show UPV test results of mortars at elevated temperatures. Although the use of both basalt powder and fibres in mortars resulted in a slight decrease in UPV values before exposure to heat, all series exhibited UPV values higher than 3.5 km/s and can be classified as excellent according to [23]. As the exposure temperature increased, the UPV values decreased dramatically. A favourable effect of basalt powder was noticed beyond 600 °C. This is attributed to the different mineral composition of the siliceous sand and basalt powder. It is well known that quartz polymorphically changes from alpha quartz to beta quartz at the temperatures between 550 °C and 600 °C, which causes volume expansion and damage in the cement matrix structure. In this manner, it can be said that the higher replacement ratio of sand with basalt powder provides a higher resistance at 800 °C. The addition of fibres did not greatly affect the UPV values. The only distinctive development obtained by fibre addition was noticed in the reference series at 800 °C. The UPV of basalt and polypropylene fibre reinforced reference samples at 800 °C was almost two times higher compared to plain mortars. This can be attributed to the exposure temperature that is over the melting point of PP fibres and causes a detrimental effect at the interface between the BF fibre and matrix.

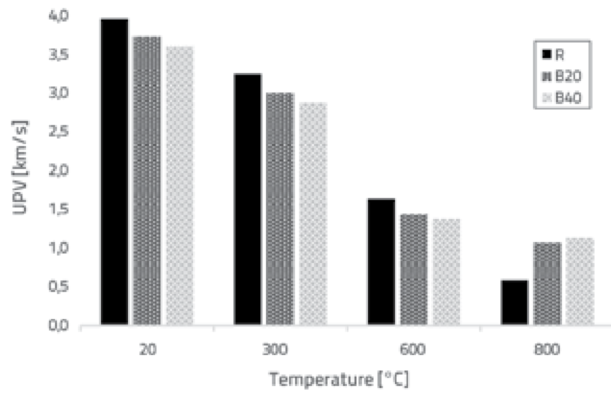

Figure 3. UPV values of reference mortars and mortars with basalt powder

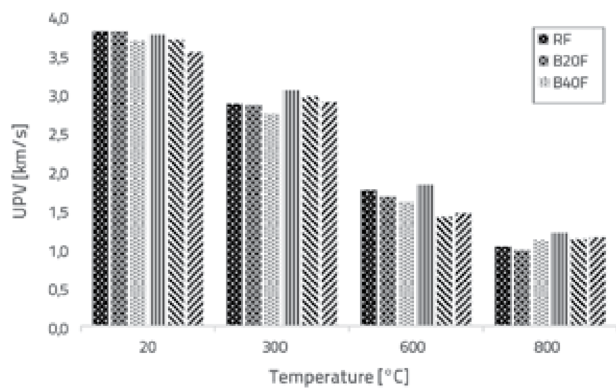

Figure 4. UPV values of fibre reinforced mortars

3.2. Mechanical properties

3.2.1. Compressive strength

Compressive strength test results are presented in Table 3. The change in compressive strength of mortars depends on mix design and temperature the samples are exposed to. Test results show that the compressive strength of mortars before heating varied between 40 MPa and 47 MPa. The compressive strength was not significantly affected by the basalt powder replacement ratio. However, the addition of basalt fibre resulted in a slight increase in compressive strength. This finding is in agreement with the study performed by Kizilkanat et al. [24] where the effect of basalt fibre on compressive strength of concrete is explained. The highest compressive strength (47 MPa) was exhibited by B20BF, while the lowest one (40 MPa) was exhibited by B20.

Table 3. Compressive strength results of mortars [MPa]

Temperature [°C]	R	B20	B40	RF	RBF	B20F	B20BF	B40F	B40BF
20	42.8	39.5	42.3	42.6	46.5	46.4	47.0	41.7	41.3
300	39.3	36.4	37.0	30.0	33.2	38.2	39.0	32.2	31.4
600	16.2	19.2	20.4	16.1	16.8	26.9	21.4	23.6	20.4
800	13.3	15.1	16.0	12.6	8.2	11.3	14.3	14.4	12.4

The relative residual compressive strength of mortars subjected to high temperatures is shown in Figures 5 and 6. The reduction in compressive strength occurred when the specimens were exposed to 300 °C, and the residual compressive strength dramatically decreased with further increase in temperature. For example, compressive strength decreased by about one half at 600 °C due to the thermal mismatch between the aggregate and the matrix phase interface.

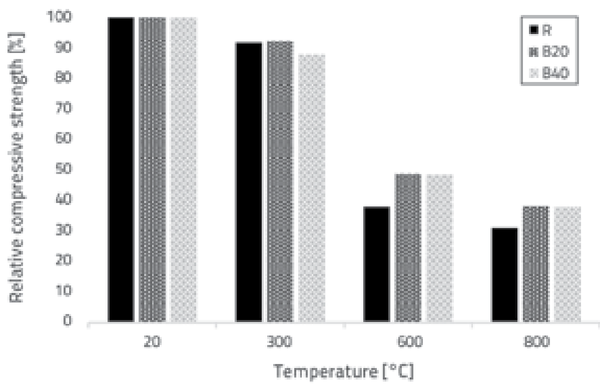

Figure 5. Relative residual compressive strength of basalt powder added mortars at elevated temperatures

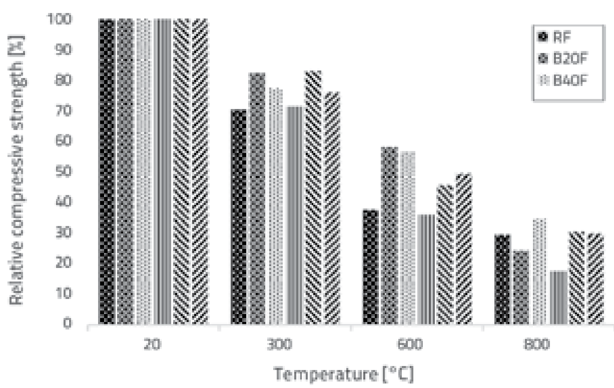

Figure 6. Relative residual compressive strength of fibre reinforced mortars at elevated temperatures

The strength loss (≈10 %) of the mortars without fibres was lower compared to the mortars reinforced with fibres (between 17 % and 31 %) at 300 °C. Although the expected positive effect of basalt powder replacement was not seen at 300 °C, its favourable contribution was observed at higher temperatures such as 600 °C and 800 °C. It was recorded that B20 and B40 series retain approximately 49 % of their initial compressive strength at 600 °C and 38 % at 800 °C, while the reference mortar (R) retains 38 % and 31 % of its initial compressive strength at the same temperatures. Different replacement ratios of sand in mixes without fibre addition did not change the strength reduction rate. A negative effect of the basalt powder (causing denser microstructure) is found to be less than its positive effect (stability at high temperatures) in mortars subjected to elevated temperatures. Since the basalt powder substitution ratio of 20 % and 40 % had no significant effect on compressive strength at higher temperatures, the sand replacement ratio can be chosen as 20 % for the mortars being susceptible to high temperatures in real-life conditions.

Polypropylene and basalt fibres were used in mortars in order to diminish the expected negative effect of basalt powder. In this case, it was observed that sand replacement with basalt powder increased the durability of mortars when exposed to heating. Although the compressive strength of fibre reinforced mortars gradually decreased with heating, the residual strength of R and B20 samples dropped below that of the fibre reinforced mortars at 600 °C. In contrast, it is interesting to note that the retained compressive strength of mortars without fibre reinforcement at 800 °C is higher than that of the fibre reinforced mortars.

When we compare the type of fibre addition, no distinctive behaviour was observed between polypropylene and basalt fibre reinforced mortars at 300 °C. When the temperature was raised up to 600 °C, PP fibre added specimens showed better performance. At 800 °C, the strength reduction was between 18 % and 35 % and B40F mix retained the highest residual strength compared to other mixes.

3.2.2. Flexural strength

Flexural strength test results are given in Table 4. Bending test results showed the same tendency as in the compression test. It can be seen in Table 4 that the flexural strength performance of mortars mainly depends on the fibre type and the exposed temperature rather than on the basalt powder substitution. Test results show that flexural strength of mortars before heating ranges between 6.4 MPa and 8.4 MPa. As expected, both basalt powder substitution and fibre addition had positive effect on the flexural strength.

The relation between the relative strength loss and elevated temperature is shown in Figure 7 and Figure 8. As illustrated in these figures, the flexural strength decreases dramatically after

Table 4. Flexural strength results for mortars [MPa]

Temperature [°C]	R	B20	B40	RF	RBF	B20F	B20BF	B40F	B40BF
20	6.4	7.2	8.1	7.0	8.0	8.4	7.7	7.9	7.4
300	4.0	4.6	4.6	3.7	4.6	4.1	4.6	3.5	4.5
600	0.6	1.3	1.4	1.2	2.5	2.1	1.8	1.8	1.7
800	0.5	0.7	0.6	0.6	1.1	0.6	1.0	0.9	0.6

heating to 600 °C, but decreases only gradually beyond this temperature. Considering the sand replacement, it can be said that although basalt powder increased the flexural strength of unheated specimens, there is no favourable effect on flexural strength after heating. The replacement of siliceous aggregate by 20 % to 40 % of basalt powder caused higher strength loss compared to specimens produced without basalt powder at 300 °C. However, the basalt powder replacement has led to an opposite trend at 600 °C. At this temperature, the relative residual strength loss for B20 and B40 series was measured as 18 % and 15 %, respectively, while the reference had only 9 % of its initial strength.

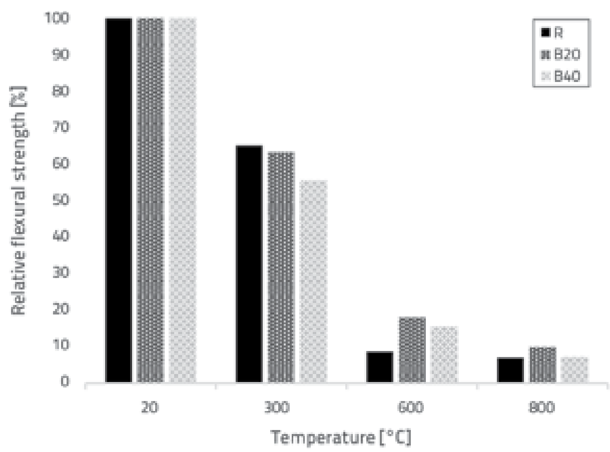

Figure 7. Relative residual flexural strength of basalt powder added mortars at elevated temperatures

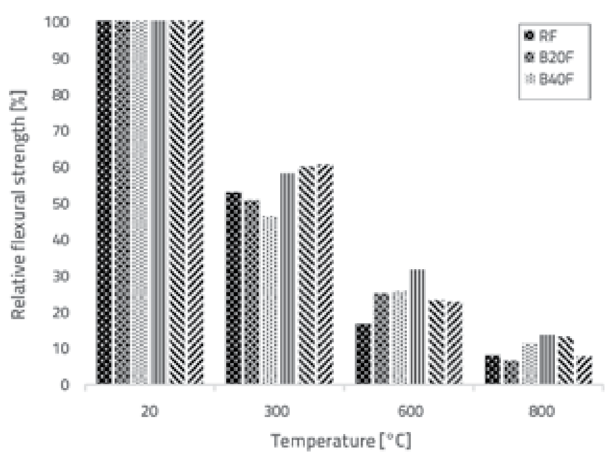

Figure 8. Relative residual flexural strength of fibre reinforced mortars at elevated temperatures

As basalt powder causes generation of high pore pressure capable of triggering explosive spalling with its higher fineness than sand, the polypropylene fibre was used in this study to avoid this phenomenon. The effect of polypropylene and basalt fibres on flexural strength of mortars was different at various temperatures. As basalt fibre plays a dominant role at 300 °C and 800 °C, PP fibre governs the flexural strength at 600 °C where the elastic strain energy reaches maximum value due to the vapour pressure [25]. This is due to the same behaviour of PP fibre under high temperature as explained in Section 3.1. The strength loss of BF added mortar series was about 40 % at 300 °C. On the other hand, the strength loss of PP fibre added mortar series ranged between 47 % and 54 % at the same temperature. When the exposure temperature increased to 600 °C the usage of PP fibre seemed to be more effective than the BF considering the basalt powder incorporated mortar series. Compared to the mortars without fibre, the strength loss of mortar with fibres was lower at 600 °C. Beyond this temperature, the contribution of fibres was negligible.

3.2.3. Fracture energy

Representative load-displacement curves recorded during bending tests of B20F mortar samples for each exposure temperature are shown in Figure 9. An accurate average load-displacement curve was obtained using the procedure suggested in [24, 26, 27]. The fracture energy was calculated from the area under the load-displacement curve according to RILEM suggestions [28].

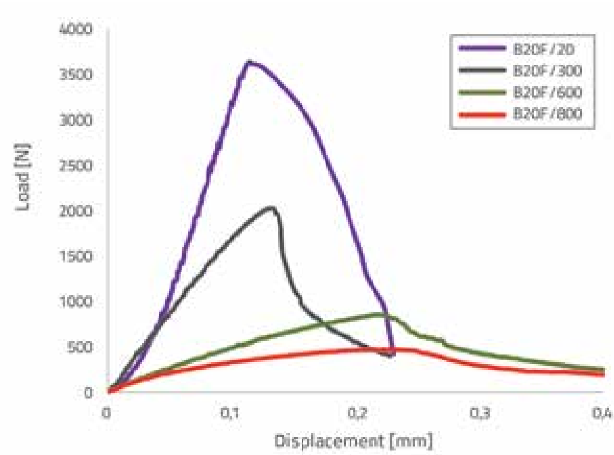

Figure 9. Load-displacement curves of B20F mix after exposure to elevated temperatures

As can be seen in Figure 9, the initial slope of load-displacement curve decreases while the temperature increases, which means that the rigidity of mortar is largely affected by temperature. This is due to the micro-crack formation on mortar with an increase in temperature.

The response of toughness to high temperatures is illustrated in Figure 10. The toughness of samples ranged between 224 J/m^2 and 462 J/m^2 at room temperature. The contribution of basalt fibre was found to be higher than that of the polypropylene fibre. This can be attributed to the faster load pick up ability of basalt fibre provided by higher strength and stiffness compared to the polypropylene fibre [29].

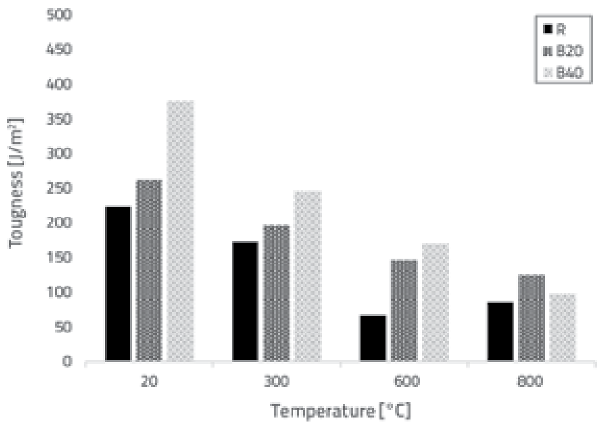

Figure 10. Load-displacement curves of B20F mix after exposure to elevated temperatures

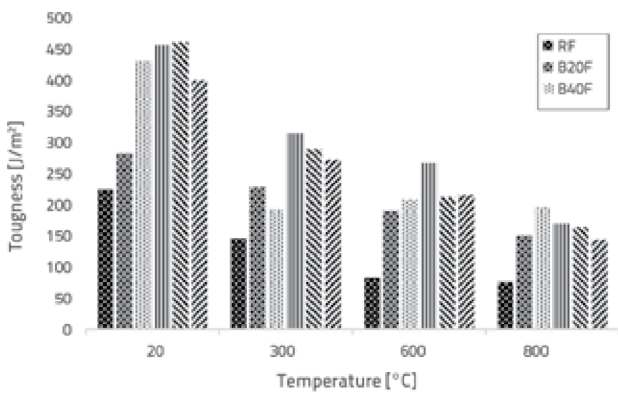

Figure 11. Load-displacement curves of B20F mix after exposure to elevated temperatures

At elevated temperatures, the toughness of all series was lower compared to the toughness tested at room temperature. The effect of PP and BF on mortar toughness at elevated temperatures can be seen in Figure 11. The figure clearly shows that BF addition significantly contributed to toughness at elevated temperatures; however, PP fibre did not cause a significant difference after 300 °C because of the low melting temperature. A similar trend was also observed on mixes in which sand was replaced with basalt powder.

4. Conclusions

The effect of elevated temperatures on mortar specimens was investigated in this study. Mortar samples with different compositions were prepared and exposed to elevated temperatures such as 300, 600, and 800 °C. The change in porosity, ultrasonic pulse velocity, compressive strength, flexural strength, and fracture energy, was investigated. The conclusions obtained from the experimental study are listed below:

- The porosity of the samples gradually increased when heating up to 800 °C, regardless of the amount of basalt powder and the type of fibre. Substituting 20 % of basalt powder with sand improved the performance of mortars at all temperatures.
- Although 40 % basalt powder replacement has higher porosity increment at elevated temperatures than 20 % basalt powder replacement ratio, the addition of PP fibres resulted in lower porosity increment for B40F compared to B20 mixes. The porosity was not significantly affected by the addition of BF.
- As the exposure temperature increased, the UPV values decreased dramatically. Favourable effect of basalt powder was noticed beyond 600 °C. The UPV values were not greatly affected by the addition of fibre.
- The reduction in compressive strength occurred when the specimens were exposed to 300 °C, and the residual compressive strength dramatically decreased as the exposure temperature increased.
- The different replacement ratios of basalt powder in mixes without any fibre addition did not change the strength reduction rate. PP fibre added specimens showed better performance when the temperature was raised up to 600 °C.
- Bending test results showed the same tendency as in the compression test. It was seen that the flexural strength performance of mortars mainly depends on the fibre type and temperature exposure, rather than on the basalt powder substitution ratio. The flexural strength decreased dramatically after heating to 600 °C, but decreased gradually beyond this temperature.
- The flexural strength loss of BF added mortar series was about 40 % at 300 °C. On the other hand, the strength loss of PP fibre added mortar series ranged between 47 % and 54 % at the same temperature. When the exposure temperature increased to 600 °C, the use of PP fibre seemed to be more effective than the BF considering the basalt powder incorporated mortar series.
- The contribution of BF to toughness of mortar was found to be higher than the PP fibre. BF addition significantly contributed to toughness at elevated temperatures. On the other hand, PP fibre did not cause a significant difference after 300 °C.

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