

Experimental Investigation of Black Scoria-Type Volcanic Aggregate Concrete Exposed to 600 °C at Early Age

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Abstract:

To study the influence of the use of imported black scoria volcanic aggregate in normal concrete, when exposed to high temperatures, as a substitute for a natural gravel medium. The volcanic aggregate was introduced from China as black scoria-type material owing to their dark color, rough texture, and porous volcanic characteristic. Concrete samples were cast cubes, cylinders and reinforced prisms. Explanation: The cubes were used to check for compressive strength, the cylinders were to determine splitting tensile strength and reinforced prisms, with 400 mm length, were tested for load–deflection behavior as small beam like elements All the specimens were tested at age 14 days. Specimens were divided into four groups. The first group was tested directly without heating and served as the control group. The rest of the groups were subjected to 600 °C for 15, 30, and 60 minutes, respectively, prior to testing. It was determined that concrete mechanical and structural performance was largely decreased by exposure to 600 °C. As a result, under exposure for 15, 30, and 60 minutes, the mean compressive strength decreased from 31.0 MPa for the control specimens to 14.5, 11.0, and 9.5 MPa, respectively. For similar exposure times the splitting tensile strength decreased from 3.46 MPa to 1.91, 1.16 and 0.59 MPa. The load–deflection results also demonstrated a decrease in stiffness and load-carrying capacity with the increase in the heating duration. The control prism achieved approximately 58 kN and prisms subjected 15, 30 and 60 minutes, 46, 33 and 31 kN. Data presented in this study demonstrate that the duration of heating has a substantial impact on the residual behavior of concrete containing black scoria type volcanic aggregate. The steepest decrease was after 600 °C, while the prolonged exposure was followed by even greater deterioration. This was ascribed to evaporation of moisture, dehydration of cement hydration products, thermal microcracking, the weakening of the aggregate–paste and steel–concrete bond. The study shows that although black scoria-type volcanic aggregate concrete can retain some load carrying capacity when heating, its mechanical and flexural performance is strongly reduced under 600 °C exposure, especially for longer durations.

Keywords — concrete, compressive strength, elevated temperature, 600 °C, splitting tensile strength, load–deflection, , volcanic aggregate.

I. INTRODUCTION

Concrete is typically manufactured with cement, water, fine aggregate, and natural coarse

aggregate like gravel or crushed stone. This coarse aggregate usually comprises a significant share of concrete volume and significantly affects strength, stiffness, density, durability, and thermal

behavior. Volcanic rocks have also been utilized as aggregates with respect to concrete, partly because of the increasing demand for natural gravel, but primarily simply due to the desire to develop novel sources of aggregate.

These materials are composed of mineralized lava sources such as basalt, scoria, pumice, and rocks from lava and volcanic crystalline phases. The material properties in these materials are much different in physical mass and shape, and they have distinct properties, including mechanical ones. Denser basaltic volcanic rock tends to be stronger, less porous, and scoria and pumice tend to be more vesicular and lightweight. Cai et al, [1]. reported that scoria aggregate concrete possesses much lower density and better fire resistance than conventional concrete. Their research also indicated that scoria concrete was better at preserving its residual compressive strength after thermal treatment than normal concrete. Scoria aggregate concrete preserved approximately 50% of its original compressive strength, and normal concrete about 44% of its original compressive strength at 600 °C. The high-temperature properties of volcanic aggregate concrete are particularly crucial since volcanic rocks originate from cooled lava or pyroclastic materials and are usually more thermally stable than some standard aggregates. Still, porous volcanic stones may absorb more water and may lose workability unless the mixing water is adjusted otherwise. Choi et al.[2] reported that basalt-based recycled aggregate had absorption values near 3–5%, mainly for porosity and irregular aggregate shape. This suggests that consideration of volcanic (or basaltic) aggregates is key to concrete mix design for safe application. Yin and Ma[3] discussed the application of volcanic stone in ultrahigh-performance concrete, and also, the pores of volcanic stone can become filled with mortar, causing a mechanical interlocking effect at the interface of the aggregate. This interlock may enhance interfacial resistance, but the porous nature of the volcanic stone may also decrease the compressive strength depending on the replacement value and composition of the mix. Although the researchers studied UHPC and not regular concrete, the same type of interfacial

zone can illuminate the behavior of normal concrete where black volcanic stone is involved. The damage of concrete upon exposure to high temperature is of several sorts, which include free water evaporation, dehydration of cement hydration products, microcracking, and thermal incompatibility for the aggregates of the two, as well as loss of bond between the aggregate and the cement paste. Tufail et al.[4] investigated concrete containing distinct aggregate types and showed that the compressive strength, tensile strength, and modulus of elasticity declined with increasing temperature. They found that aggregate type has a substantial influence on residual concrete performance after heating. Choosing the temperature of 600 °C is extreme and applicable to fire-damaged concrete. Concrete suffers a major loss of strength and cracking at this temperature, of course. Research on concrete at elevated temperature has observed that the mechanical properties are significantly reduced at 600 °C due to the degradation of cement paste, vapor pressure inside the cement, and thermal cracking. As a result, 600 °C is considered an appropriate temperature to investigate the residual behavior of concrete containing imported black volcanic stone. The duration of heating is also an important thing. A specimen that is heated up to 15 minutes may show surface and partial internal damage, but the longer exposure times, like 30 and 60 minutes, allow heat to invade even deeper into the specimen. Thus, the compressive strength, tensile strength, stiffness, and load-carrying capacity are likely to suffer from a prolonged exposure time. Furthermore, higher heating duration might also increase deflection and decrease post-heating structural stiffness of reinforced prism specimens. This study contrasts with many previous studies, as the specimens were evaluated and heated at 14 days after casting and not at, for example, the more common age of 28 days. Hydration is still maturing on 14 days, and the concrete may contain more free water than mature concrete does. This may render the specimens more sensitive to heating-induced damage, particularly at 600 °C; thus, the findings of this study help to inform preliminary studies considering the early-age residual behavior of

concrete enriched with imported black volcanic stone.

II. METHODOLOGY

A. Materials description

The concrete used in this study was produced with usual Portland cement, natural fine aggregate, imported black scoria-type volcanic coarse aggregate, water, and a super plasticizer. It was imported from China as black volcanic aggregate, and as replacement for the traditional natural gravel. The material was therefore a scoria-type volcanic aggregate, which is classified primarily based on its black color, rough surface texture and porous volcanic appearance.

B. Mix design

The mix design used in the experimental were cement content was 410 kg/m³, the fine aggregate content was 680 kg/m³, and the coarse volcanic aggregate content was 685 kg/m³. To improve the workability of the mixed material, the water-cement ratio was calculated to 0.33 and the superplasticizer dosage of about 0.5% by the cement weight.

C. Preparation of Process of Mixing and Casting and Casting.

The concrete components were weighed with selected mix proportions prior to mixing. The solid matter in the dry material, such as cement, sand, and black scoria-type volcanic coarse aggregate, was first mixed in order to create a uniform distribution (the size of the cement fine particles). After which, water was slowly added in the process of mixing, in conjunction with the required concentration of superplasticizer. This process was repeated until the concrete looked even in color and consistency. Fresh concrete was tested for workability by slump test following mixing. The concrete was then transported into the supplied molds for cubes, cylinders, and reinforced prisms. They were filled with molds in different layers, and each layer was compacted appropriately to reduce entrapped air and facilitate consolidation. Using a trowel, the specimens was prepared to a smooth surface at the top surface. The samples were preserved in the molds for a period of initial setting and then were demolded

and cured to test age after casting. Prisms at 400 mm length were cast and reinforced as mini beam-like elements during testing. Longitudinal bars were arranged he specimen to ensure spacing and shear reinforcement. The reinforcement set up was the same for all prism specimens, so where load-deflection behavior differs, it remains mostly due to the concrete condition and time length of thermal exposure. All these steps were shown in fig1.



Fig. 1 Step of casting samples and concrete textures.

D. Experimental Program and Specimen Grouping.

The experiment was conducted in order to investigate the behavior of concrete with imported black scoria-type volcanic aggregate before as well as after the formation of the ash in the concrete under elevated temperatures. The age at which all specimens were tested was after the 14th days following casting. In a four-group study, specimens were examined according to the exposure condition as explains in Table 1.

TABLE I
DESCRIPTION OF GROUPS.

Group	Exposure condition	Testing age	Tests performed
Group 1	No heating	14 days	Compression, splitting tensile, load-deflection
Group 2	600 °C for 15 min	14 days	Compression, splitting tensile, load-deflection
Group 3	600 °C for 30 min	14 days	Compression, splitting tensile, load-deflection
Group 4	600 °C for 60 min	14 days	Compression, splitting tensile, load-deflection

All heating's were subjected to the same temperature at 600 °C as shown in fig2, while burning was performed 14 days later following casting. The specimens were cooled after heating and subjected to testing. The objective of varying exposure duration was to investigate the degree of

influence of different heating to residual strength in relation to structural behavior of the concrete. A comparison between unheated and heated specimens was made to estimate the residual performance of the black scoria-type volcanic aggregate concrete.



Fig. 2 Samples under exposure to temperature

E. Slump Test.

The slump test was performed immediately after mixing to examine the workability of the fresh concrete. New concrete was laid in the slump cone in various layers and compacted during filling. When the cone was lifted vertically, the height of the concrete reduced was recorded as the slump value. Following the slump test photograph, the concrete displayed a visible slump and remained in cohesive shape following the removal of the cone. A rough slump value of about 130 mm showed the medium-to-high workability of the mixture as shown in fig3. This degree of workability was appropriate for filling the cube, cylinder and prism moulds, particularly since the prisms housed reinforcement cages which required good flow and compaction around the steel bars. Superplasticizer was applied to increase the workability of this mixture, even though black scoria-type volcanic aggregate material has a rough and porous texture. This was an important consideration because volcanic aggregate might reduce the workability due to water absorption and internal friction increases in the mix.



Fig 3. Slump test.

F. Compressive Strength Test.

The compressive strength test was done on concrete cube specimens aged 14 days. Two cubes were tested directly without heat for the reference group. The heated groups were set to expose cube specimens to 600 °C for a specific time (15, 30 or 60 minutes) and investigated after cooling as shown in fig4. During the testing, each cube was placed centrally between the plates in the compression testing machine. Gradually the load was applied to the cube until failure occurred. The compressive strength test for the concretes was conducted where the impact of volcanic aggregate and heating duration on the load-carrying capacity of the concrete matrix were analyzed. Compressive strength of specimens which were exposed to 600 °C was expected to be weakened compared to unheated specimens because of loss of moisture, dehydration of cement paste, thermal cracking; the bonding between the aggregate and mortar, when it was weakened at 600 °C.



Fig 4. Compressive strength test.

G. Splitting Tensile Strength Test.

The splitting tensile strength test was done on cylindrical concrete samples. The cylinder was examined directly at 14 days for the unheated group. For heated samples, the cylinders were heated to 600 °C for 15, 30, or 60 minutes before being tested as shown in fig5. For this test, the cylinder was horizontally placed between the testing machine loading plates. The full test was performed and the load applied along the length of the cylinder until the splitting failure occurred. Standard splitting tensile strength equation was applied to determine the splitting tensile strength according to the maximum load when running the test. The importance of the splitting tensile test lies in the fact that tensile strength influences the cracking behavior of concrete. Since increased temperature leads to microcracking and decreases the cement paste and interfacial transition zone, it was anticipated that the splitting tensile strength would respond more to heat than compressive strength. Consequently, the test results were employed in order to investigate the cracking resistance of the black scoria-type volcanic aggregate concrete pre- and post-heating



Fig 5. Splitting tensile strength test.

H. . Load–Deflection Test for Reinforced Prism Specimens.

The load-deflection effects were verified under loading, the prisms of the reinforced concrete were considered. Both prism specimens extended to 400 mm length and were supported with longitudinal steel bars and transverse stirrups as highlighted in the reinforcement images. These specimens were utilized in describing small parts of reinforced concrete beam elements. In the load–deflection stage of a test, each prism was

installed in the test set-up and gradually loaded. During the testing, the load and the midspan deflection are recorded. The load–deflection curve was then plotted to assess the stiffness of each specimen, cracking behavior, maximum load and post-cracking response. The prism specimens were tested at unheated condition directly at 14 days, and were used as the reference condition. Other prism specimens had been examined at 600 °C for 15, 30, and 60 minutes before testing. The four group load–deflection curves comparison was utilized to examine the impact of heating time on structural behavior of the reinforced prisms. Exposure to 600 °C was anticipated to impart decreasing initial stiffness and maximum load capacity of the prisms. It can be assumed that the longer heating times would induce higher deflections at the same load level due to the higher incidence of cracks and weakening in the bond between the concrete and reinforcement. Accordingly, load-deflection curves gave crucial information about the concrete residual structural behavior due to thermal treatment.

III. RESULTS AND DISCUSSIONS

A. Compressive strength

The compressive strength test was performed on cube samples at the age of 14 days. Group 1 underwent direct testing without heating, and Groups 2, 3, and 4 were exposed to 600 °C for 15, 30, and 60 minutes, respectively, before testing. Two cube specimens were tested for each group, and the results are shown in Table 2 and Table 3.

Table 2. Compressive strength results.

Group	Exposure condition	Cube 1 strength MPa	Cube 2 strength MPa	Average strength MPa
Group 1	Unheated, tested at 14 days	34	28	31.0
Group 2	600 °C for 15 min	14	15	14.5
Group 3	600 °C for 30 min	12	10	11.0
Group 4	600 °C for 60 min	10	9	9.5

Table 3. Residual and losses Compressive strength

Group	Average compressive strength MPa	Residual strength %	Strength loss %
Group 1	31.0	100.0	0.0
Group 2	14.5	46.8	53.2
Group 3	11.0	35.5	64.5
Group 4	9.5	30.6	69.4

After exposure to 600 °C, the compressive strength is observed to decrease significantly, while the mean compressive strength of the unheated sample was 31.0 MPa at 14 days. The strength was then reduced to 14.5 MPa with a residual strength of 46.8% after 15 minutes of heating. When heating time was increased to 30 minutes, the mean strength was reduced to 11.0 MPa (representing 35.5% of the original strength). Of the 600 °C specimens exposed for the maximum period of 60 minutes, the lowest average strength was noted, with an average strength of 9.5 MPa, corresponding to 30.6% residual strength as shown in fig6. These findings showed that increasing the heating time led to the progressive reduction of compressive strength. The reduction can be caused by moisture evaporation, dehydration of the cement hydration products, thermal cracking, and weakening of the bond between the cement paste and the black scoria-type volcanic aggregate. The maximum amount of loss from the heat was recorded after 15 minutes of first exposure, revealing that the initial step of heating at 600 °C caused severe damage to the concrete matrix

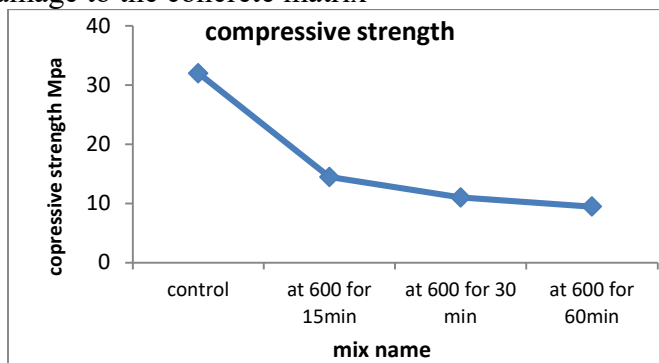


Figure 6. Compressive strength results.

B. Splitting tensile strength

The splitting tensile strength test of the specimens was performed on cylindrical specimens at 14 days of age. The control specimen underwent direct, unheated test, whereas the other specimens were exposed to 600 °C for 15, 30, and 60 min (respectively) before a test. The findings are presented in Table 3.

Table 4. Splitting tensile strength results and residual strength.

Group	Exposure condition	Splitting tensile strength MPa	Residual strength %	Strength loss %
Group 1	Control, unheated	3.46	100.0	0.0
Group 2	600 °C for 15 min	1.91	55.2	44.8
Group 3	600 °C for 30 min	1.16	33.5	66.5
Group 4	600 °C for 60 min	0.59	17.1	82.9

The splitting tensile strength obtained after 600 °C showed a significant reduction, and the control specimen had a splitting tensile strength of 3.46 MPa at 14 days. After 15 minutes of heat at 600 °C, tensile strength decreased to 1.91 MPa and also the residual strength occurred to be 55.2%. When this exposure time rose to 30 min, the tensile strength diminished to 1.16 MPa, accounting for 33.5% of the original value. The lowest value was found after 60 minutes of exposure, where the splitting tensile strength fell to 0.59 MPa, which is only 17.1% of the control tensile strength. The increase in heating time led to the gradual decrease of splitting tensile properties observed by these results. This reduction was largely attributed to moisture evaporation, internal vapor pressure, dehydration of cement hydration products, thermal microcracking, and interfacial transition zone weakening of the cement paste with black scoria-type volcanic aggregate. The splitting tensile strength was more sensitive to

thermal exposure than the compressive strength, significantly so after 60 min, indicating that tensile properties could be strongly influenced by microcracking caused by temperatures. The loss in strength were shown in fig7.

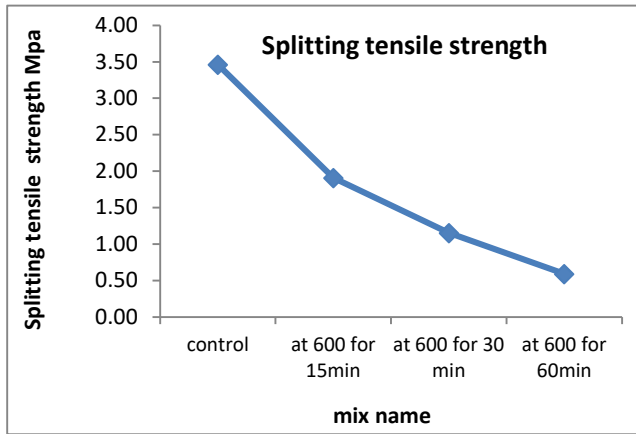


Fig 7. Splitting tensile strength results.

7. Load-deflection respond

As shown in fig 8 and Table 5, the load–deflection curves were a definite impact of 600 °C exposure on the structural response of the reinforced prism specimens. The maximum load capacity was found for the control prism, reaching around 58 kN at a deflection of approx 3.0 mm. Maximum load (approximately 46 kN) and deflection (approximately 4.0 mm) was observed after exposure to 600 °C for 15 minutes. The increase in exposure time to 30 min further reduced the maximum load to approx 33 kN. The prism was exposed for 60 min and reached up to about 31 kN, however it was deflected in a much larger deflection of about 5.3 mm. These findings suggest that longer heating period decreased the stiffness and load bearing capacity and increased deformation. These reduction was attributed to thermal cracking, dehydration of cement hydration products, loss of tensile strength, and the possible weakening of the bond between concrete and reinforcement. The load–deflection behaviour confirmed the compressive and splitting tensile strength results: a greater reduction of mechanical properties occurred at 600 °C as the exposure continued for longer time intervals.

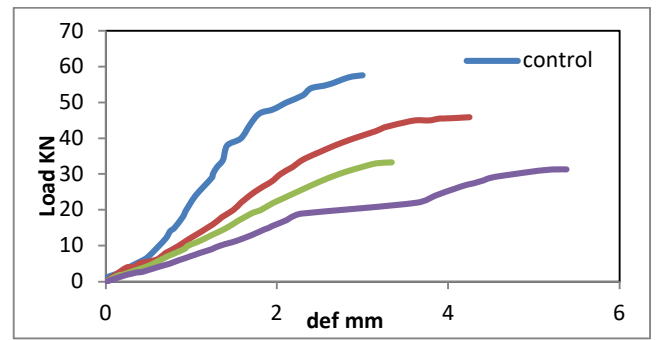


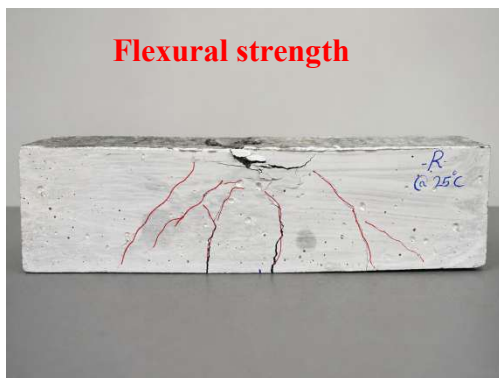
Fig. 3 shows an example of an image with adequate

Group	Exposure condition	Approx. maximum load kN	Approx. deflection at maximum load mm	Behavior
Group 1	Control	57.62	3	Highest stiffness and strength
Group 2	600 °C for 15 min	45.86	4.25	Moderate reduction in stiffness and load
Group 3	600 °C for 30 min	33.32	3.34	Clear strength and stiffness loss
Group 4	600 °C for 60 min	31.36	5.38	Lowest stiffness and highest deflection

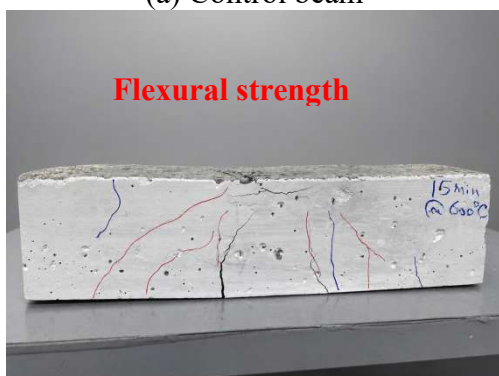
C. Failure mode

To identify the effect of temperature-induced cracking pattern and structural behavior, the failure modes of the reinforced concrete prism specimens were studied after load testing. From the visual observation, flexural failure was observed in the control specimen and a specimen exposed to 600 °C for 15 minutes, shear failure in the specimens exposed to 600 °C for 30 minutes and 600 °C for 60 minutes. Thermal exposure had a substantial influence on the failure mode of the reinforced prism specimens. Both the control

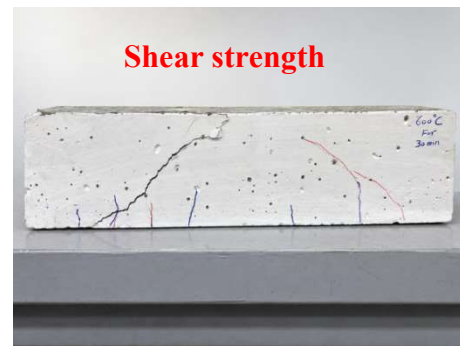
prism and specimen studied at 600 °C for 15 min failed in flexure owing to the presence of predominantly vertical cracks within the tension zone close to midspan. The specimens exposed to 600 °C for 30 min and 600 °C for 60 min failed under shear, which led to the most noticeable diagonal cracks that went from the support region to the loading point. The change in failure mode showed the impact of increasing the exposure duration that contributed to great deterioration in the internal structure of concrete. The shift from flexural to shear failure is possibly due to the significant decrease of tensile strength, the increase in thermal cracking, the decrease in the interfacial transition zone, and the bond between concrete and reinforcement weakening. Since shear failure is more brittle than flexural failure, the findings indicate that extensive 600 °C exposure not only weakened and stiffened the prism specimens, but also the structural response is less safe and ductile.



(a) Control beam



(b) at 600°C for 15 min



(c) at 600°C for 30 min



(d) at 600°C for 60 min

Fig 9. Failure mode for all groups.

IV. CONCLUSIONS

The reported concrete with imported black scoria-type volcanic aggregate had an acceptable compressive strength at 14 days before heating. However, 600 °C was found to lead to substantial declines in compressive strength, splitting tensile strength, and the prism load–deflection effect. The decrease was greater when the exposure time was longer (15 to 60 min). Splitting tensile strength was the most influenced property, suggesting that heat-induced microcracking strongly affected the tensile behavior of the concrete. The results of the reinforced prism verified that high temperature diminished the stiffness and load-carrying capacities and increased the deflection. As such, black scoria-type volcanic aggregate can be used in ordinary concrete, though its post-exposure high temperature performance needs to be critically evaluated for structural uses in concrete.

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