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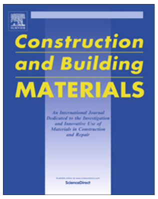

Review

A review of residual strength properties of normal and high strength concrete exposed to elevated temperatures: Impact of materials modification on behaviour of concrete composite

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HIGHLIGHTS

- Evaluation of residual strength properties of normal and high strength concrete exposed elevated temperatures.
- Stress–strain behaviour after concrete exposure to elevated temperature.
- Unstressed residual testing method.

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ABSTRACT

This study presents a review of residual strength properties of normal and high strength concrete exposed elevated temperatures: the implication of natural and recycled aggregates, the addition of mineral admixtures, and fibre. The influence of supplementary cementing materials such as fly ash, blast furnace slag, silica fume, metakaolin, and commonly used fibers: steel and polypropylene on concrete residual compressive and tensile strength, modulus of elasticity, and stress–strain behaviour after exposure to elevated temperature were considered. The data obtained from previous laboratory test results are compiled to understand the role played by room temperature compressive strength and varying concrete mix material composition on residual mechanical properties of concrete. A statistical analysis of normalized residual mechanical strength (the ratio of the original strength at room temperature to that obtained after the exposure to temperature) was carried out to rank and determine the significance each factor on the residual mechanical properties of concrete. The study showed that properties of concrete such as compressive strength, tensile strength, and stress–strain behavior with three testing methods: preloaded and tested hot, unloaded and tested hot, and unloaded and tested at room temperature (unstressed residual) have been explored by researchers. This study reported the unstressed residual testing method so as to allow uniformity and a common baseline for comparison. This review has shown lacking areas where there is need for extensive research regarding the residual strength properties of concrete subjected to elevated temperatures, especially concrete containing admixtures and fibers. The outcome of this review will be beneficial to researchers, engineers and constructors in the field of civil engineering and construction domain.

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1. Introduction

It is well known that concrete is the most used manmade materials in the world, and the second most consumed substance in the world after water. Concrete, being the most used manmade materials in the world and the second most consumed substances in the world behind water is of high demand for different construction purposes and will continue to be in demand far into the future [1,2]. A world without concrete is hard to imagine [3]. Concrete is a composite material, made up of different constituents which include binder materials such as cement and supplementary cementitious materials, aggregates, and water [4].

The retained properties of concrete after cooling down from exposed high temperatures are generally referred to as its residual properties. These properties change substantially within elevated temperature range associated with exposed fire and can be influenced by factors such as time of exposure, characteristics and material composition of concrete [5], type of fire load [6], aggregates type and size, type of cement/binder paste, and water/cement ratio [7]. It is common practice to vary the material composition of concrete in order to produce its different forms and improve on certain properties both at ambient temperature and after exposed elevated temperature [8]. The various forms of concrete range from normal and lightweight concrete, natural and recycled aggregate concrete, normal strength (20 to 50 MPa), high strength (50 to 120 MPa) and ultra-high strength (exceeding 120 MPa) concrete, plain and fiber-reinforced concrete, and conventional and high-performance concrete [9–14].

Fire represents one of the most severe environmental conditions that affect concrete [11]. The heat generated from fire generally causes a high-temperature gradient in concrete. The temperature gradient induced on concrete causes chemical and physical reaction such as dehydration of cement paste, decomposition of aggregates, mass loss, deformation and strength loss [16,17] which in turn negatively affects the mechanical and thermal properties of concrete [15]. Concrete mechanical properties are adversely affected when exposed to elevated temperature, it begins to experience initial degradation at a temperature range 200 °C – 300 °C, this deterioration has been observed to continue with further increase in temperature, hence reducing the strength and stiffness of structure [19,20].

The further possible usage of heated concrete due to fire would depend on its residual performance. Hence, it is of great importance to know the behavior of concrete after exposure to high temperatures. The residual mechanical properties of concrete have been studied in literature and several researchers have carried out experimental works to study their influencing factors at high temperatures. This report bases its conclusions from the review of previous experimental obtained results for normal and high strength concrete made from natural and recycled aggregates. Relevant professional committee reports and standard codes such as ACI 216R-90 [17], CEN Eurocodes [18], ASCE [19] and ASTM [20] on variations of concrete properties at elevated temperature was set as benchmarks. Influencing factors including the addition of different types of supplementary cementitious materials (SCMs), fibers, and aggregates types used in the concrete mix are the main focus in this report. The elevated temperature range adopted by most authors is between average room temperature of 23 °C to 800 °C, however, few authors tested concrete strength up to 1000 °C and 1200 °C.

1.1. Mechanical properties of concrete at elevated temperature

Structures made from concrete material are exposed to elevated temperatures during a fire scenario. The relative properties of concrete after such exposure are very important in terms of its serviceability and failure criteria [21]. The main mechanical properties of concrete that are of interest after exposure to elevated temperatures include compressive strength, tensile strength, modulus of elasticity, and stress–strain response [5]. These properties are commonly used to measure the extent of strength loss and deterioration of concrete at elevated temperatures. Many researchers have used three different main approaches to carry out laboratory investigations on the mechanical properties of concrete exposed to high temperatures. The unloaded and tested hot, preloaded and tested hot where specimens are crushed at targeted high temperature (hot temperature test), and the residual unstressed tests where specimens are allowed to cool down to room temperature before being loaded to failure (unstressed residual test) [25,26]. From literature, common specimen sizes used varies from 70 × 70 mm, 100 × 100 mm, and 150 × 150 mm cubes for compressive strength test [27–31]. Some researchers also used cubes size of 100 × 100 and 150 × 150 for tensile strength test [32,30,33]. Cylindrical specimens size ranges from Ø50 × 100 mm, Ø100 × 200 mm, and Ø150 × 300 mm are commonly used for both compressive and splitting tensile strength test [34–37].

Concrete mechanical properties generally decrease with increasing temperature, concrete loss approximately 25% of its original compressive strength when heated to 300 °C and about 75% when exposed to temperature above 600 °C [38,11,8,39,36]. A similar trend has been observed by different authors for tensile strength loss in concrete after elevated temperature [30,35,40–42]. For modulus of elasticity, it is generally considered to be the most affected mechanical properties of concrete after exposure to elevated temperature. The degradation of modulus of elasticity is much faster than that of compressive and tensile strength [37,16]**.** However, axial strain in concrete generally increases with increasing temperature, indicating severe deformability and ductility of concrete at higher temperature range [38,39]. The summarised data of concrete mechanical strength properties after exposure to elevated temperature considered in this report is presented in Table 1**.** The concrete type distribution considered in this report is presented in Fig. 1. Residual mechanical properties including compressive strength, split tensile strength, modulus of elasticity, and stress–strain behaviour of concrete after elevated temperatures are discussed in this section Table 2.

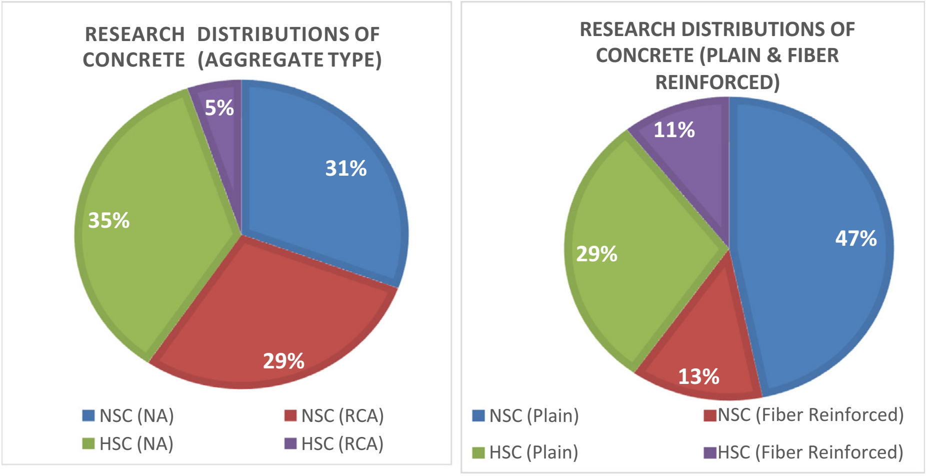
1.2. Residual compressive strength of concrete

Compressive strength of concrete at room temperature depends on water-cement ratio, curing conditions, aggregate type and size, admixture types, and type of stress among others [48]. Besides, factors such as concrete strength at room temperature, rate of heating, duration of exposure to fire, and fire load equally influenced the residual compressive strength of concrete at elevated temperatures [5]. The residual compressive strength of concrete is of particular interest in the fire safety design of structures. Hence, several previous researchers have investigated concrete compressive strength behavior at high temperatures. The main findings from the experimental results of previous researchers on the relationship of residual compressive strength of normal strength concrete after exposure to elevated temperatures and comparison with

Table 1
Summary of the researches carried out on the residual mechanical properties of concrete.

Refs	Year	Concrete Type	Sample size (mm)	Aggregate Type	Aggregate Replacement (% by Vol)	w/b	SCMs (% mass content in cement)	Fiber (% Conc Vol), mass content, kg/m3	Test Temp.	Mechanical Properties tested
[43]	**2008**	HSC	Ø102 × 204	NA	NA: 100	0.30, 0.35, 0.40	Silica Fume: 0, 6, 10	Nil	20, 100, 200, 300, 600	*f*cu,
[44]	**2010**	HSC	Ø102 × 204	NA	NA: 100	0.30, 0.40	Silica Fume: 0, 6, 10	Nil	20, 100, 200, 300, 600	*f*cu, *f*t
[45]	**2015**	NSC	Ø100 × 200	NA	NA: 100	0.35	FA: 40, 50, 60	Nil	20, 100, 200, 300, 400, 500, 600, 700, 800, 900	*f*cu, *f*t
[46]	**2019**	NSC	Ø100 × 200	NA	RA: 0, 30, 60, 100	0.5	GP: 20	StF: 0.5	25, 200, 400, 600	*f*cu, *f*t
[36]	**2020**	NSC	100 × 100 × 100	NA	NA	0.5	nS: 0, 3, 6, 8	BF: 0, 1, 2, 3 kg/m3	20, 200, 400, 600	*f*cu, *f*t
[47]	**2020**	NSC	100 × 100 × 100	NA	NA: 100	0.5	Nil	StF: 0, 0.25	20, 100, 200, 300, 400, 600, 700, 800	*f*cu, *f*t, fshear
[8]	**2020**	NSC	100 × 100 × 100	NA	NA: 100	0.5	Nil	StF: 0, 0.25	20, 100, 200, 300, 400, 600, 700, 800	*f*cu, *f*t, fshear

NSC- Normal strength concrete, HSC- High strength concrete, NA- Natural aggregate, RA- Recycled concrete aggregate, FA- Fly ash, GGBS- Ground granulated blast furnace slag, SF- Silica fume, GP – Glass power, MP- Marble powder, RHA- Rice Hush Ash, StF- Steel fiber, PPF- Polypropylene fiber, MK- Metakaolin, nS- Nano silica, *f*cu- Compressive strength, *f*t- Spilt tensile strength, E- Modulus of elasticity, ε- Strain, fshear - Shear strength.



(a) (b)

Fig. 1. Concrete type distributions (a) base on aggregate type (b) base on fiber addition.

Table 2
Summary of the normalized Residual compressive strength with increase temperature.

Source	CA	Aggregat e Type/Re pacement (%)	Conret e type	w/b	SCMs Type: (% mass content in cement)	FiberTpye: %Conc. Vol./(mass content, kg/m^3)	Room Temp Comp. Str	NORMALIZED Residual Compressive Strength (Mpa) at Test Temperatures (°C)											
								23	100	200	300	400	500	600	700	800	900	1000	1200
[47]	CL	NA:100	HSC	0.43	–	–	**67.60**	1.00				0.79		0.74		0.61			
	CL + RA	RA:20	HSC	0.44	–	–	**67.70**	1.00				0.75		0.75		0.53			
	RA	RA:100	HSC	0.49	–	–	**63.60**	1.00				0.80		0.77		0.67			
[32]	CL	NA:100	NSC	0.45	–	–	**34.10**	1.00	1.05	0.85	0.67	0.57							
[52]	CL	NA:100	NSC	N/S	–	–	**43.50**	1.00					0.92						
	CL + RA	RA:30	NSC	N/S	–	–	**46.20**	1.00					0.84						
[49]	CL	NA	NSC	0.55	–			–	**33.00**	1.00	0.81			0.70			0.36		
	SG	NA	NSC	0.55	–			–	**33.50**	1.00	0.89			0.87			0.48		
	SG + RA	RA:25	NSC	0.55	–			–	**32.00**	1.00	0.78			0.73			0.41		
	RA	RA:100	NSC	0.55	–			–	**31.00**	1.00	0.84			0.92			0.50		
[50]	NSA	NA	NSC	0.43	–			–	**38.20**	1.00	0.85	0.91	0.80	0.66	0.59	0.46	0.27		
	NSA + R A	RA:30	NSC	0.43	–			–	**39.60**	1.00	0.78	0.77	0.72	0.58	0.59	0.37	0.23		
	RA	RA:100	NSC	0.43	–			–	**33.30**	1.00	0.88	0.85	0.93	0.98	0.81	0.54	0.23		

* = Only Normalised compressive strength (at room and elevated temperature) was provided. CA- Coarse aggregate, C- Crushed stone, RA- Recycled aggregate, CL- Crushed limestone, SG- Siliceous gravel, NCA- Natural coarse aggregate, NSA- Natural siliceous aggregate, Q-Quartzite, GR- Granite, RBA- Recycled brick aggregate, CaA- Calcareous aggregate. NSC- Normal strength concrete, HSC- High strength concrete, FA- Fly ash, PFA- paper sludge ash, MK- Metakaolin, GGBS- Ground granulated blast slag, SL- Silica fume, nS- Nano silica, StF- Steel fiber, PPF- Polypropylene fiber.

relevant standards are presented in Fig. 2. This report analyzed the normalized residual compressive strength values, which is the ratio of compressive strength at elevated temperature to the initial compressive strength at room temperature in other to quantify the behavior of concrete after thermal exposure. The unstressed residual state test results were considered to eliminate the possible effect of different test modalities on results [49–59]. The compressive strength of concrete decreases with a rise in temperature as observed in Fig. 1, however, varying response of concrete to elevated temperature is attributed mainly to different compressive strength value at room temperature, aggregate type, and water-cement ratio used for concrete mix. Generally, strength reduction is due to changes in the physical and chemical compositions of concrete upon heating, which leads to micro cracking and internal stress from the thermal expansion of aggregates [60–64]. Furthermore, changes in hydrothermal conditions through the loss of free and adsorbed water as temperature rises, loosen mortar matrix, and deterioration of ITZ at elevated temperatures up to 300 °C contributed to initial strength loss [65,41,66,63]. Above 400 °C, attributed causes of strength reduction include dehydration and disintegration of hydration products of calcium hydroxide (CH) [55] and loss of stiffness due to the decomposition of calcium silicate hydrate (CSH) gel at temperature around 600 °C [39]. Within the temperature range of 600–800 °C, thermal mismatch between cement matrix and aggregates, coarsening of pore structures, and instability of aggregates due to decomposition of calcium carbonate leads to further strength reduction [59,67–68].

However, some researchers observed increased residual compressive strength at initial elevated temperature range of 100 – 300 °C, followed by a sharp decrease in strength. Increased compressive strength was observed at 100 °C [31], 200 °C [48,30], 250 °C [40] and at the temperature range of 200 – 300 °C [62]. Dry hardening of cement paste caused by further hydration of cement and internal steam curing due to hot vapor through internal autoclave condition at this temperature range was highlighted as possible reasons for the increased strength at initial elevated temperature range [46,43,58,39,69,70].

Overall, the residual compressive strength can be categorized within three main temperature range: (1) Room temperature – 350 °C characterized with initial stabilizing and regaining stage, (2) 350 °C – 800 °C characterized with strength loss stage. (3) Over 800 °C is characterized by total strength loss of concrete strength [5].

1.3. Residual tensile strength of concrete

Concrete is weak in tension; hence, cracks can easily propagate under tensile load [64]. Tensile strength retained in concrete after elevated temperature caused by fire is an important property of concrete structural members, especially where fire-induced spalling may occur [40,41].

From available literature, tensile strength of concrete decreases with increase elevated temperature [71,32,36,30]. As the temperature rises, similar to compressive strength experience, physical and chemical changes that take place due to hydrothermal processes lead to a reduction of the tensile strength [35]. The internal moisture evaporation and crystal decomposition of concrete become more serious as reduction in chemically bonded water continues due to dehydration and partial decomposition of C-A-S-H gel, the compactness of the mortar loosen, thus, splitting tensile strength decreases [72,42]. Fig. 3 shows a high positive correlation between normalized residual compressive and split tensile strength of concrete after exposed temperatures. The addition of fibers and supplementary cementitious materials in concrete mix has been observed to significantly reduce residual tensile strength loss thereby improving its residual tensile strength after exposed

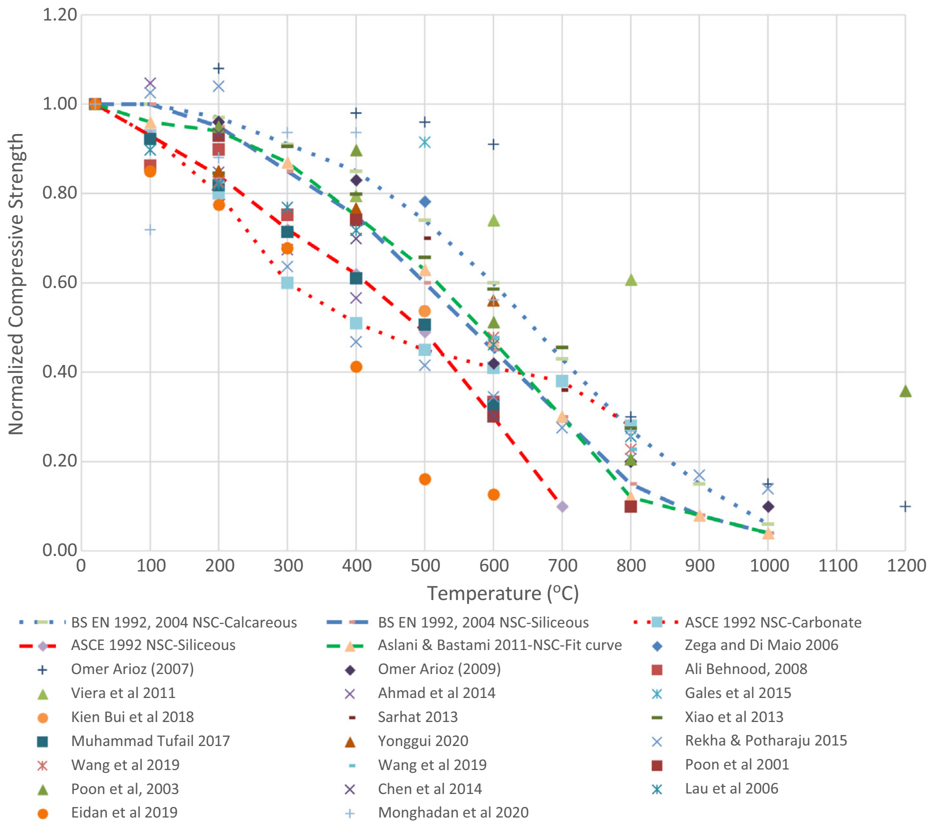


Fig. 2. Relationship of normalized residual compressive strength of normal strength concrete (NSC) after exposed temperature.

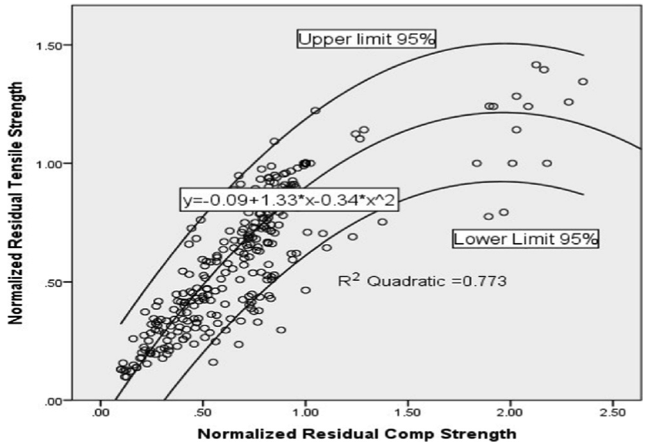


Fig. 3. Normalised residual tensile strength vs normalized residual compressive strength of concrete after exposed temperatures.

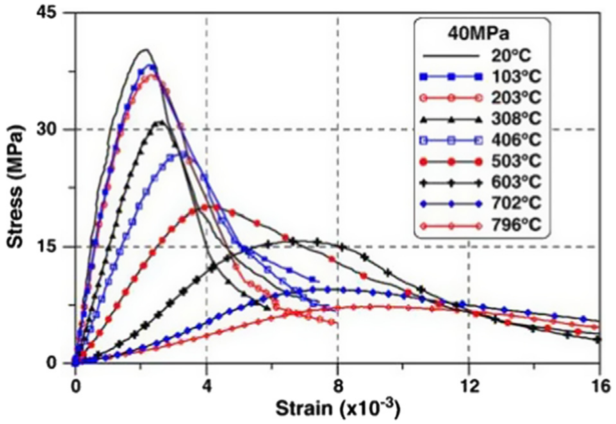


Fig. 4. Residual stress–strain relationship of concrete after exposed temperatures [69].

elevated temperature [34,39,71,73–74]. Generally, concrete experience greater degradation in terms of splitting tensile strength compare to compressive strength after heating cycle (see Fig. 6). This has been attributed to the fact that splitting tensile strength is more sensitive to thermal and micro-cracks than the compressive strength [54,33]. Hence, concrete with high residual tensile strength performs better and possess higher resistance to crack propagation and explosive spalling at elevated temperatures [33]. Table 3 gives the summary of the normalized residual tensile strength of concrete with and without addition of supplementary cementitious materials and fibers.

1.4. Residual Stress-Strain behavior of concrete

The relationship between induced stress and deformation (strain) in concrete behaves differently depending on the level of exposed temperature (see Fig. 4). The effect of temperature changes on the compressive strength of concrete also affects the stress–strain behavior of concrete. Smoother stress–strain curve is produced as temperature increases [45,75]. This indicated that, under the same amount of induced compressive stress on concrete, there is increased corresponding strain as exposed temperature increases. Xie et al 2018 [39] studied the response of axial compressive stress–strain relationship at elevated temperature range

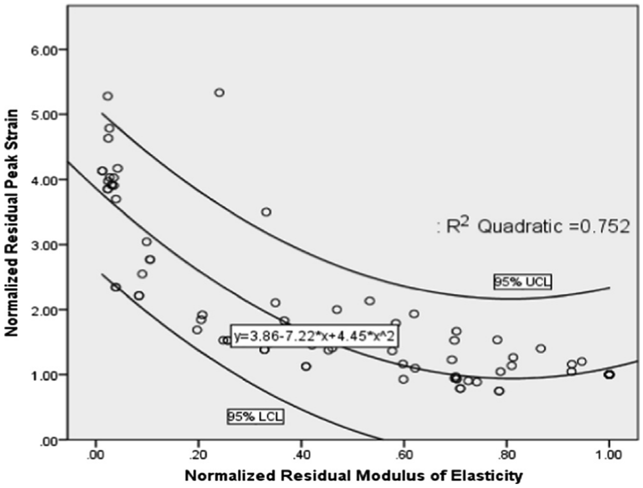


Fig. 5. Relationship between normalized peak strain and modulus of elasticity of concrete.

25 °C – 800 °C. Similar to common observation by previous researchers [76,43], peak strain, which is the strain corresponding to ultimate stress applied, increases as the temperature increases from 25 °C to 800 °C. Fig. 4 shows the stress–strain response of 40 MPa concrete after exposure to different elevated temperatures [69]. Increased peak strain indicates higher ductility of concrete under elevated temperature. Data from previous researches is used to investigate the relationship between normalized residual peak strain (deformation) and modulus of elasticity (stiffness) of concrete after exposed temperatures. A quadratic relation of significant correlation is obtained as presented in Fig. 5.

1.5. Residual modulus of elasticity

The modulus of elasticity of concrete, similar, to other mechanical strength properties is affected by the level of exposed temperature. Modulus of elasticity is generally considered to be the most affected mechanical properties of concrete during exposure to elevated temperatures. The degradation of modulus of elasticity is much faster than that of compressive strength and tensile strength [43,20]. This has been attributed to the loss of free water and effect of crack development on concrete specimens exposed to high temperature [75,9,52,61,30]. Concrete exposed to high temperatures exhibits severe loss of modulus of elasticity compared to those kept at room temperature. This severe loss is experienced rapidly with an initial rise in temperature as opposed to what is observed for residual compressive and split tensile loss. The normalized modulus of elasticity of concrete after exposed temperature is presented in Table 4. Chen et al. [37] observed a considerable initial decrease in modulus of elasticity as temperature rise to 400 °C and further decrease with increasing temperature, but with slower degradation rate at temperature above 600 °C. Concrete can lose most of their elastic modulus until 400 °C heating–cooling cycle [9,52,43,61,37]. While at higher temperature range, Xie et al [39] concluded that the elastic modulus of concrete has little difference between 600 °C and 800 °C due to the collapse of the resistance to the compressive deformation at 600 °C resulting in little further drop in elastic modulus of concrete at 800 °C. The high rate of degradation of concrete modulus of elasticity after exposure to elevated temperature infers that high temperature has a considerably damaging effect on its microstructure [37]. The summary of statistical details of mechanical strength properties of concrete at room and elevated temperature are presented in Table 5 while the response of residual mechanical strength properties of concrete with rise in temperature is shown in Fig. 6.

1.6. Factors influencing residual mechanical strength properties of concrete

The major factors affecting concrete mechanical strength properties are similar to those that affect its residual strength properties when exposed to elevated temperature, however, their behavior differs from that observed at ambient temperature. This report focuses on the influence of concrete compressive strength at room temperature with consideration of normal and high strength concrete only, addition of supplementary cementitious materials (fly ash, GGBS, metakaolin, silica fume, and nanosilica), aggregate types (natural and recycled coarse aggregate) as well as the addition of commonly used fibers (steel and polypropylene) in concrete exposed to high temperature. Residual compressive strength of concrete behaves in a similar way to residual split tensile strength after elevated temperature [69,76–77]. However, the splitting tensile strength of concrete is more sensitive to high

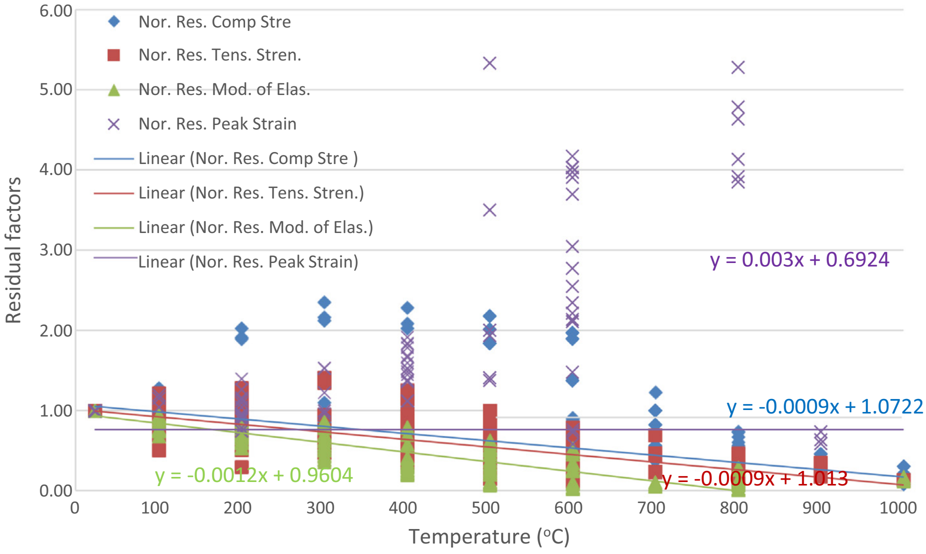


Fig. 6. Performance of concrete residual mechanical properties after exposed temperatures.

Table 3
Summary of Research for Residual Tensile strength of concrete after exposure to high temperature.

Refs	CA	Aggregate Type/Replacement (%)	Concrete type	w/b	SCMs Type: % mass content in cement	Fiber Tpye: % Conc. Vol./(mass content, kg/m3)	Room Temp Split. Tens. Str	NORMALIZED Residual Splitting Tensile Strength after Test Temperatures (°C)										
								23	100	200	300	400	500	600	700	800	900	1000
[32]	CL	NA:100	NSC	0.45	-	-	**2.70**	1.00	1.22	1.09	0.95	0.85						
[34]	CL	NA	NSC	0.55	-	-	**2.52**	1.00	0.88	0.77	0.65	0.54	0.42	0.25				
	Q	NA	NSC	0.55	-	-	**3.22**	1.00	0.89	0.79	0.68	0.58	0.47	0.31				
	GR	NA	NSC	0.55	-	-	**4.05**	1.00	0.91	0.82	0.73	0.64	0.56	0.42				
[28]	RA	RA:100		0.45			**2.60**	1.00		0.92		0.73		0.35		0.15		
		RA:100		0.45			**3.00**	1.00		0.77		0.63		0.40		0.20		
		RA:100		0.45			**2.70**	1.00		0.93		0.63		0.30		0.26		
CONCRETE WITH FIBER																		
[44]	CL	NA	HSC	0.33	SF + FA	-	**8.10**	1.00		1.00		0.43		0.21		0.10		
		NA	HSC	0.33	SF + FA	StF: 0.6%												
		NA	HSC	0.33	SF + FA	PP fiber: 0.6%	**8.10**	1.00		1.00		0.44		0.43		0.28		
		NA	HSC	0.33	SF + FA	PP: 0.3% + StF: 0.3%	**9.90**	1.00		0.99		0.83		0.59		0.38		
[56]	CL	NA	NSC	0.60	-	PP: 1.5kg/m3	**2.10**	1.00				0.71		0.33		0.14		
		NA	HSC	0.35	SL:10	PP: 2.5kg/m3	**3.90**	1.00				0.67		0.26		0.20		
[58]	CA	NA	NSC	0.5	-	-	**3.03**	1.00	0.69	0.30	0.59	0.83	0.50	0.25	0.23			
		NA	NSC	0.5	-	StF: 0.25%	**3.88**	1.00	0.72	0.71	0.64	0.70	0.59	0.34	0.24			

* = Only Normalised split tensile strength (at room and elevated temperature) CA- Coarse aggregate, C- Crushed stone, RA- Recycled aggregate, CL- Crushed limestone, SG- Siliceous gravel, NCA- Natural coarse aggregate, NSA-Natural siliceous aggregate, Q- Quartzite, GR- Granite, RBA- Recycled brick aggregate, CaA- Calcareous aggregate. NSC- Normal strength concrete, HSC- High strength concrete, FA- Fly ash, PFA- paper sludge ash, MK- Metakaolin, GGBS- Ground granulated blast slag, SL- Silica fume, nS- Nano silica, StF- Steel fiber, PPF- Polypropylene fiber.

Table 4
Summary of Normalized Residual Modulus of Elasticity concrete after exposed temperature.

Source	CA	Aggregate Type/RCA Replacement (%)	Concrete typ (NSC/ HSC)	w/b	Admixture dosage (%) mass content in cemen	Fiber (% conc vol.) mass content, kg/m3	Room Temp Mod. of Elast. (GPa)	NORMALIZED Residual Modulus of Elasticity (Gpa) after Test Temperatures (°C)										
								23	100	200	300	400	500	600	700	800	900	1000
[47]	CL	NA:100	HSC	0.43	–	–	43.70	1.00				0.30		0.25		0.12		
	CL,RA	RA:20	HSC	0.44	–	–	36.70	1.00				0.33		0.27		0.11		
	CL,RA	RA:50	HSC	0.46	–	–	40.40	1.00				0.31		0.25		0.11		
	CL,RA	RA:100	HSC	0.49	–	–	33.20	1.00				0.34		0.26		0.11		
[52]	CL	NA:100	NSC	N/A	–	–	22.30	1.00					0.45					
	CL,RA	RA:30	NSC	N/A	–	–	21.85	1.00					0.33					
	RA	RA:100	NSC	N/A	–	–	21.85	1.00					0.24					
CONCRETE WITH FIBER																		
[30]	CL	NA	HSC	0.30	–	–	46.40	1.00	0.89	0.61	0.43	0.23						
[58]	CA	NA	NSC	0.5	–	–												
		NA	NSC	0.5	–	Steel fiber: 0.25%, len 30 mm, dia 0.8 mm												
[56]	CL	NA	NSC	0.60	–	PP: 1.5 kg/m3, len 12 mm, dia 31-35um	35.70	1.00			0.51		0.11		0.07			

Table 5
Statistical data on mechanical strength properties of concrete at room temperature and after exposed temperature.

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Concrete Type (NSC)	1111						
Concrete Type (HSC)	748						
Room Temp. Comp. Strength (MPa)	1793	125.65	10.35	136.00	56.8789	27.78054	771.758
Normalized Residual Comp Strength	828	2.27	0.08	2.35	0.7238	0.34093	0.116
Room Temp. Tensile Strength (MPa)	715	8.42	1.48	9.90	3.7237	2.02976	4.120
Normalized Residual Tensile Strength	343	1.32	0.10	1.42	0.6682	0.30439	0.093
Room Temp. Modulus of Elasticity (GPa)	627	61.11	20.89	82.00	33.1100	11.45282	131.167
Normalized Residual Modulus of Elasticity	259	0.99	0.01	1.00	0.5264	0.35471	0.126
Room Temp. Peak Strain	253	0.65	0.15	0.80	0.3778	0.12750	0.016
Normalized Residual Peak Strain	104	4.75	0.59	5.33	1.7734	1.19295	1.423
Temperature (°C)	12	977	23	1000	502.09	313.058	

temperatures than compressive strength [72]. The residual mechanical strength properties of concrete changes substantially at different elevated temperature levels and can be further influenced by heating rate and time of exposure to fire [5,6]. The capacity of concrete to retain its mechanical strength properties after exposure to elevated temperatures is very crucial in evaluating the fire resistance of concrete structures [73].

2. Influence of concrete room temperature compressive strength

2.1. Residual compressive strength

The room temperature compressive strength of concrete plays a key role in its residual mechanical properties when subjected to elevated temperature. The residual compressive strength behavior of high strength concrete (HSC) vary differently when exposed to high temperature compared to that of normal strength concrete (NSC). HSC strength loss and degradation after elevated temperature as reported by different authors is not consistent [5]. However, some researchers observed that the effect of elevated temperature is more pronounced on high strength concrete, with higher rate of degradation and loss of compressive strength over entire temperature range [80,81]. Normal strength concrete typically loses about 10–20% and 60 – 75% of its original compressive strength when heated to temperature of 300 °C and 600 °C respectively, while high strength concrete has higher rates of original strength loss as much as 40% at temperatures up to 450 °C [76]. NSC exhibits good performance at high temperatures, it shows increased residual strength at initial temperature range 150 – 300 °C due to the effect of dry hardening and formation of heating steam with internal autoclave causing further hydration in concrete [38,5]. Generally, dehydration reactions of hydration products cause different response of concrete at elevated temperature. From ambient temperature – less than 300 °C, NSC experiences fluctuation in strength, thereafter is a gradual drop when the temperature exceeds 300 °C. Between 400 °C and 600 °C, the residual compressive strength starts to decrease drastically. Main compressive strength loss is concentrated within this temperature range. With further rise in exposed temperature, compressive strength drops to about 20% of its ambient temperature strength at 800 °C [55,42]. The compact microstructure of HSC does not easily allow for easy moisture evaporation under high temperature, this lead to build up of pore pressure, rapid developments of micro cracks and faster deterioration of strength in HSC at subjected high temperature compared to NSC [5,59,42]. Unlike normal strength concrete, HSC is characterized by explosive spalling. Spalling occurs in HSC even at a very low-temperature range 350–400 °C in HSC [77]. HSC also suffers both chemical decomposition and pore structure coarsening of the hardened cement paste when C-S-H starts to decompose at elevated temperature. It was concluded that high strength concretes suffer greater compressive strength loss than normal strength concrete at maximum exposure temperatures of 600 °C [22]. On the contrary, Poon et al [41] observed that HSC maintained a higher percentage value of residual compressive strength than NSC due to coarsening of the pore structure and increase in pore diameter, which was found to be more in NSC at elevated temperatures than in the HSC. Hence, NSC showed a gradual decrease in strength. This also agrees with Phan et al [78] results at maximum concrete core temperature of 450 °C, concrete with higher original strength (93 MPa), lower w/cm ratio retained higher residual compressive strength after exposure to elevated temperature than those with lower original strength (51 MPa) and higher w/cm ratio. The addition of SCM and Fibers improves the residual compressive strength of both NSC and HSC at elevated temperatures. (detail in section 3.2 and 3.3). The line of best fit from a regression analysis of experimental results on residual compressive strength as obtained by previous researchers considering normal and high strength concrete without addition of fiber is presented in Fig. 7**.** To quantify strength, decrease with elevated temperature, normalized residual compressive strength of NSC and HSC without fiber addition are considered and compared with relevant standards and models. Similarly, Fig. 8 shows a generalized trend of concrete normalized compressive strength response at different exposed temperatures with increasing room temperature compressive strength based on obtained experimental data from previous researches Fig. 9 Fig. 10..

2.2. Residual tensile strength

Tensile strength of NSC, similarly to compressive strength decreases with an increase in exposed temperature due to its weak microstructure allowing for initiation of microcracks. Normal strength concrete loses approximately 20% of its initial tensile strength at 300 °C and due to rapid thermal damage above 300 °C, tensile strength reduces to about 20% of its initial strength at 600 °C [5]. On the other hand, tensile strength degradation in HSC is not consistent as there are significant variations as reported by various authors. Chan et al [81] observed that mechanical strength loss (compressive and tensile strength) in high strength concrete is similar to that of normal strength concrete during exposed temperature up to 1200 °C. HSC splitting tensile strength shows an initial higher loss at 100 °C, thereafter, strength loss becomes gradual until 800 °C with an average retention of 12 – 16% of room temperature strength at 800 °C [53]. However, Laneyrie et al [82] observed an opposing trend that high strength concrete with w/c ratio 0.3 shows lower decrease of relative tensile strength with increased temperature compared to normal strength concretes with w/c 0.6 because of the better bonding at interfaces when the water content decreased. The addition of steel and hybrid fibers slows the loss of tensile strength of concrete with increased temperature [73] (details are in section 3.3).

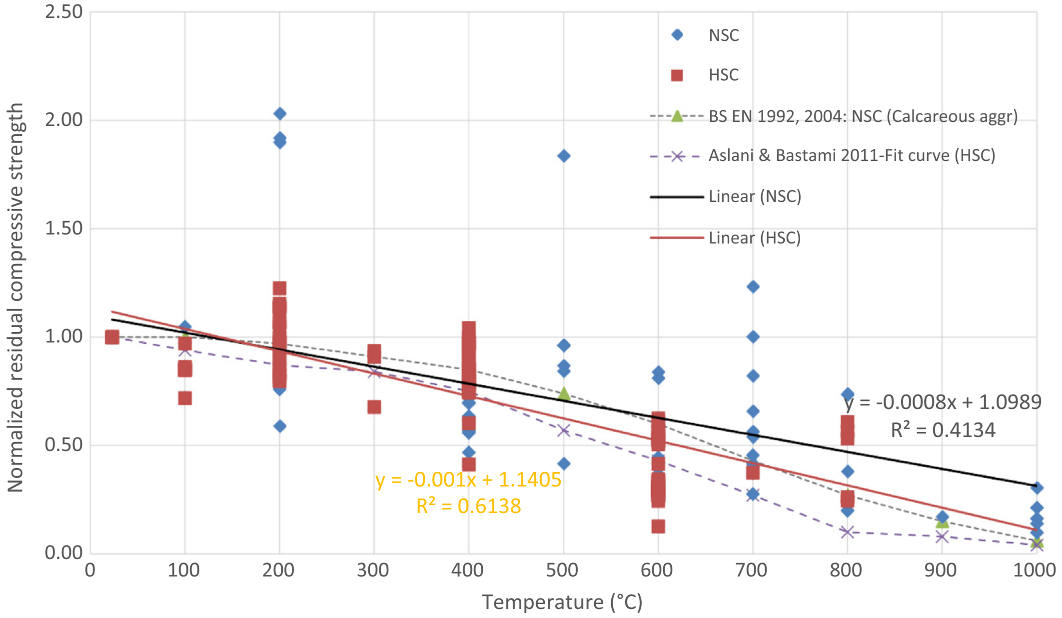


Fig. 7. 0 Normalized Residual Compressive Strength for NSC and HSC after exposed temperatures. *NSC:* [43,47,52,55,27,9,85,86]**;** *HSC:* [28,42,59,47,81].

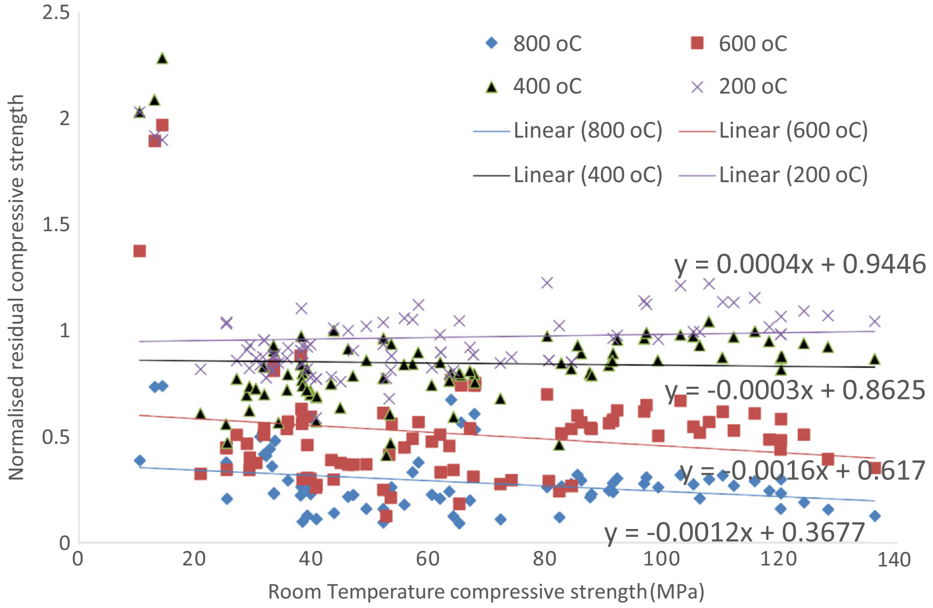


Fig. 8. Relationship between normalized residual compressive strength and compressive strength at room temperature.

2.3. Stress-Strain behavior and modulus of elasticity

Stress–strain response of concrete is often obtained alongside concrete compression strength tests. Generally, increased exposed temperature resulted to decrease in concrete ultimate peak stress and a corresponding increase in its peak strain. Previous research works revealed that the value of compressive strength of concrete at room temperature contributed significantly to the varying responses of concrete stress–strain behavior after exposure to elevated temperature. Normal strength concrete is observed to possess the highest level of ductility behavior when compared to high strength concrete at elevated temperature. This ductility indicates a smoother stress–strain curve with an overall increased peak strain as temperature rises [38]. HSC has been observed to show different stress–strain behavior from NSC during exposure to elevated temperature. HSC produced a very steep stress–strain slope at room and initial elevated temperatures, indicating brittle properties [83]. It is more difficult to achieve ductile behavior for HSC compared to normal-strength concrete at room temperature. However, for exposed elevated temperatures, Cheng et al [84] found out that high strength concrete exhibit brittle properties to an elevated temperature below 600 °C and start to show ductility behavior above 600 °C.

As earlier mentioned, Modulus of elasticity of concrete is severely affected by rise in exposed temperature. Different room temperature concrete compressive strength value affects the level of loss in its elasticity modulus at elevated temperature. Lau and Anson [23] compared the residual modulus of concrete with compressive strength range from normal, (39 MPa) medium (53 MPa) and high strength (99 MPa) concrete at different elevated temperature. They found out that normal strength concrete mix lost approximately 7% to 73% of its room temperature modulus of

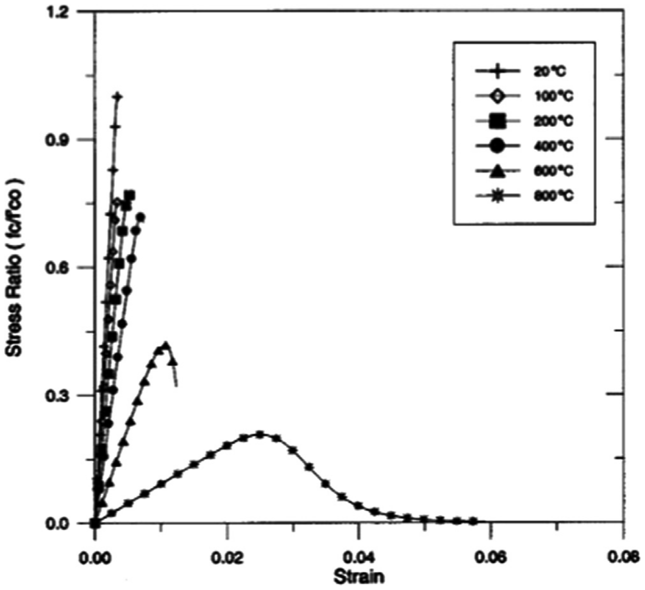


Fig. 9. Relationship of Stress–strain behavior of high strength concrete (without steel fiber) [84].

elasticity between 105 °C and 1100 °C respectively, while high strength concrete mix lost about 24% to 93% at the same temperature range. This showed that the variation in concrete modulus of elasticity losses for normal and high strength concrete is large at initial elevated temperatures. However, the impact of room temperature strength became less and the level of elasticity modulus loss becomes quite similar for NSC and HSC after exposure to higher elevated temperatures.

3. Influence of addition of supplementary cementitious materials (SCM)

3.1. Residual compressive strength

Blend of supplementary cementitious material (SCM) such as fly ash FA, silica fume (SF) grounded granulated blast furnace slag (GGBS) with cement improve the properties of concrete at both room and elevated temperatures. The summary of residual compressive strength of concrete and the influence of addition of SCM at room and elevated temperatures are presented in Table 3. Pozzolanic concretes containing fly ash (30%) and blast furnace (40%) slag gave higher retained residual strength in HSC and NSC respectively particularly at temperatures below 600 °C compared to pure cement concretes [41]. Similarly, improvement of residual compressive strength was observed in concrete with the addition of pulverized fly ash (PFA) compared to non-PFA concrete at exposure temperature range of 450 °C and 650 °C [40]. The compressive strength of high-volume fly ash concrete increased initially as the temperature increases up to 300 °C in the range of 112–136% for 60% – 40% fly ash content replacement respectively, then followed by a declining strength as temperature increases. However, greater strength loss is observed in high volume fly ash concrete [85]. For recycled aggregate concrete, addition of SCM has also proved to be beneficial on its residual compressive strength. The addition of FA causes a significant reduction in RAC strength loss at temperature up to 400 °C as a result of further hydration reaction of reactive powders in FA which is accelerated under high temperature. However, this is followed by a remarkable strength reduction at temperatures above 400 °C [24]. This strength reduction was attributed to the development of internal stresses and microcracks in both the two interfacial transition zones caused by different thermal expansion coefficients of old and new materials [86].

Besides, Kien et al [54] studied the influence of different mineral admixtures (fly ash (FA), waste paper sludge ash (PSA), silica fume (SF), metakaolin (MK) on the residual compressive strength of concrete after exposure to elevated temperature 500 °C. Residual compressive strength of RAC concrete increased by 38.45% and 35.23% with addition of 5% and 10% FA respectively. Fly ash improves the residual compressive strength of heated RAC the most followed by MK, PSA, cement, and SF. On the other hand, silica fume and nanosilica perform poorly in terms of residual compressive strength of concrete after exposure to elevated temperatures. Bastami et al [28] compared silica fume and nano silica addition in HSC, they observed that nano silica addition increase the critical temperature level for major compressive strength loss in HSC from range 400–800 °C as observed for normal HSC to 600 – 800 °C in HSC with nano silica additions indicating that nS addition is more effective than SF at elevated temperatures. Yongui et al [36] observed at

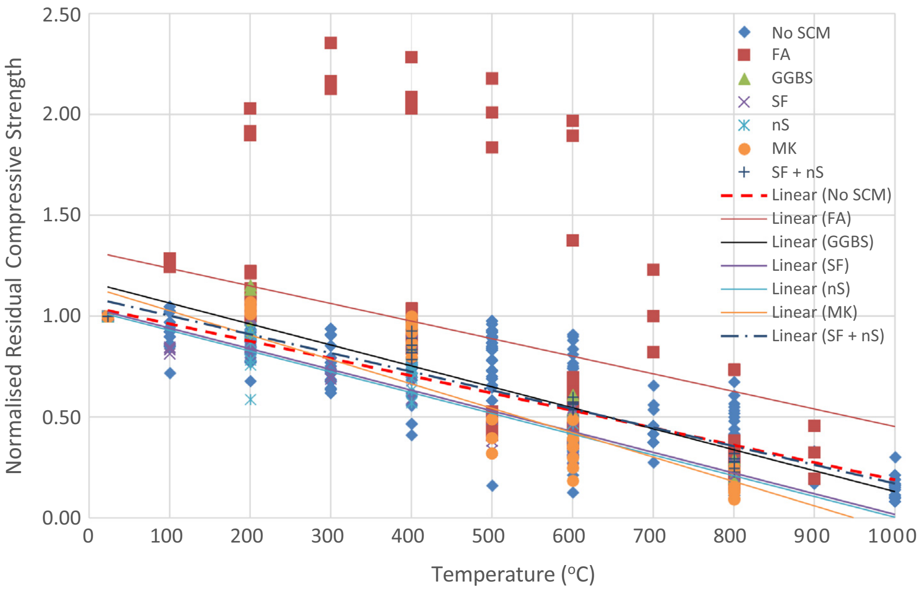


Fig. 10. Normalized residual compressive strength of concrete with different SCMs after exposed temperature.

400 ℃, as the content of nS increases, the content of the CH crystals decreases and the content of C-S-H gel increases, while the C-S-H began to decompose at 600 °C, further increase in nS content causes the pore content to increase, mortar compactness decreases and the structure gradually becomes looser. These changes in the microstructure with the content of nS at different temperatures shows the tendency for relative residual compressive strength to decrease as the content of nS increases [36]. This agrees with the conclusions of Behnood et al [44] on the effect of silica fume (SF) on the residual compressive strength of HSC which showed higher strength loss in silica fume concrete compared to only OPC concretes at temperatures up to 600 °C, but were approximately the same above 600 °C. This effect was attributed to denser transition zone between aggregates and paste due to ultra-fine particles in SF concretes which hinders easy escape of moisture. At elevated temperature, expansion of aggregates and contraction of paste developed higher stress concentrations in the transition zone that caused more sensitivity of the bonding between aggregate and paste containing SF than that of only OPC concrete leading to greater strength loss of SF concretes. The addition of mineral admixtures produces a superior and dense microstructure with less amount of calcium hydroxide that ensures a beneficial effect on compressive strength at room temperature [87]. Nevertheless, this compact microstructure leads to detrimental effects of concrete compressive strength at elevated temperature due to lower permeability that do not allow easy escape of moisture, thereby resulting in build-up of pore pressure and development of cracks [49,79]. Fig. 11 shows the relative percentage change in residual compressive strength of concrete with addition of different SCMs based on experimental data obtained by previous authors.

3.2. Residual tensile strength

There is limited literature on the trend of the residual tensile strength of concrete with addition of SCMs at exposed elevated temperatures. The use of nS was observed to be more efficient than silica fume in increasing residual tensile strength of heated concrete at higher temperatures, however, their blend in concrete improves further the residual tensile strength concrete at all elevated temperatures [28]. Although, silica fume concrete possesses good mechanical properties at room temperature, nevertheless, concrete with silica fume undergo severe tensile strength loss after exposure to 600 °C [72].

Furthermore, the influence of addition of fly ash in concrete significantly mitigates deterioration of mechanical properties and improves its resistance to spalling occurrence and cracks formation caused predominantly by the development of tensile stress under elevated temperature [88]. Khan and Abbass [50] studied the variation in tensile strength of concrete with and without fly ash at elevated temperature, they observed an increase tensile strength of range 33 – 43 % for concrete with fly ash 40 – 60% content respectively as initial temperature rises to 300 °C before declining at higher temperature level. Gao et al [89] and Shen et al [90] observed similar positive influence with addition of GGBS in concrete. The splitting tensile strength of concrete increases remarkably with the inclusion of GGBS for normal and fiber reinforced concrete respectively. Nevertheless, excessive GGBS reduces the mechanical performance of concrete [89]. This also agrees with Kou et al [91] results which showed that GGBS concrete has higher residual tensile strength compared to fly ash concrete at all exposed temperature considered. However, GGBS concrete mixtures suffered strength reduction in the range of 48 – 53 % while the strength loss for fly ash concrete range from 61 to 71% of their initial strength after exposure temperature of 500 °C. Limited research work is observed on the residual performance of GGBS concrete at elevated temperature from available literature despite its wide acknowledgment as a suitable admixture for improving strength properties of concrete at room temperature. The regression line of best fits obtained for different SCMs based on experimental results is presented for residual tensile strength in Fig. 12.

3.3. Stress-Strain behavior and modulus of elasticity

Supplementary cementitious materials addition in concrete mix has been shown to influence the behavior of stress–strain relationships in concrete exposed to elevated temperature. Kien et al [54] studied and compared the effect of different SCMs by addition and replacement methods on the stress–strain response of recycled aggregate concrete. They found out distinctly differing responses of each method. While addition method resulted in the greater

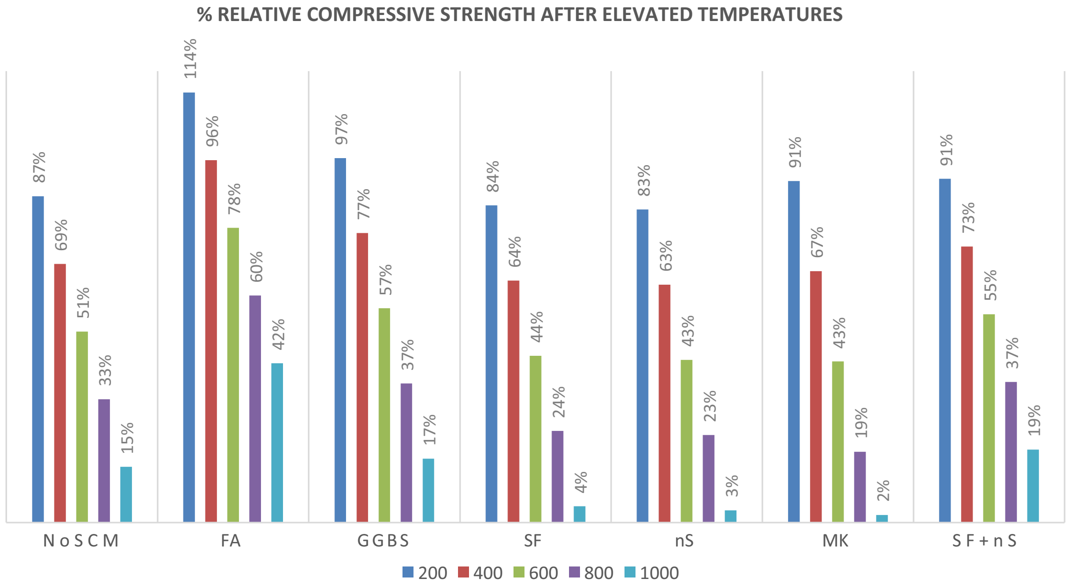


Fig. 11. Percentage relative compressive strength of concrete with different SCMs after exposed temperature.

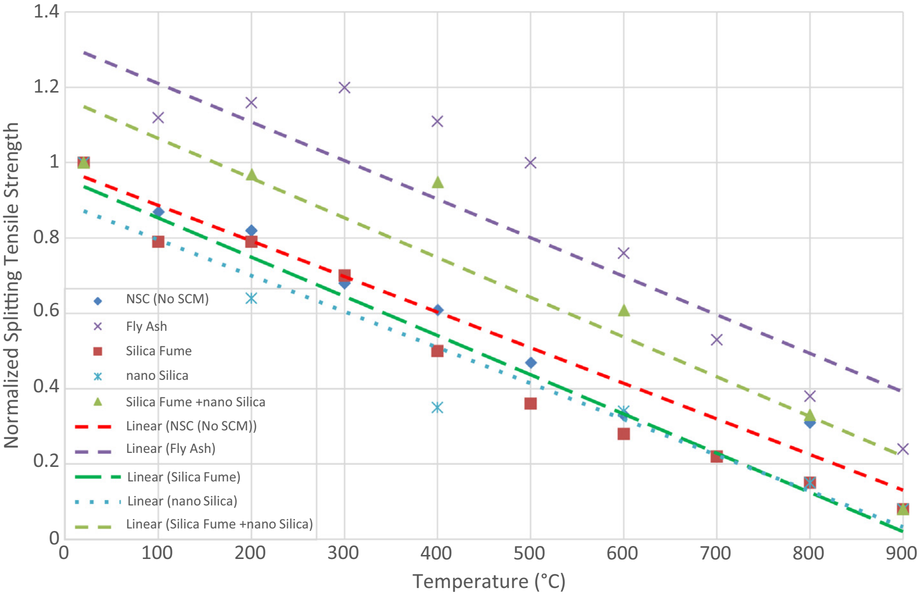


Fig. 12. Normalized residual strength for different SCM in concrete *Data extracted for* FA: [739350]; SF: [732953]; nS + SF: [28]; NSC:[2647342729].

slope of ascending branch of the stress–strain curve of concrete at elevated temperature, the stress–strain curves of RAC in the replacement method exhibited smoother and flatter stress–strain curves indicating reduced peak stress and stiffness of heated RAC with replacement method compared to that with addition method. They concluded that Fly ash enhances the stress–strain curves of heated RAC better than paper sludge ash (PSA), metakaolin, and silica fume. Furthermore, the deformability of concrete which is mostly evaluated by the value of its peak strain, with addition of mineral admixtures after elevated temperature varies with the type of concrete. Peak strain of normal concrete seems to be independent on mineral admixtures at elevated temperature [93], whereas, Kien et al [54] found out that strain in heated RAC was considerably increased with incorporation of 5 – 15% mineral admixtures due to higher residual compressive strength of RAC incorporating mineral admixtures at observed 500 °C exposure temperature. Silica fume and metakaolin increased the critical strain of heated RAC higher than that of PSA and FA.

The effect of addition of SCMs on concrete's modulus of elasticity seems to vary based on aggregate type used in the concrete mix. For normal concrete, metakaolin and silica fume do not have a significant effect on the stiffness of the concrete before and after exposure to the elevated temperatures [93]. SCMs influence on RAC residual elastic modulus depends on the type used. Kien et al [54] found out that with the addition of 5% FA in RAC, the residual elastic modulus of RAC increased by 34.61% after 500 °C exposed temperature while the replacement of 10% and 15% cement by silica fume dropped the residual elastic modulus of RAC by 6.95% and 27.3% respectively after same exposed temperature. Fly ash, Paper sludge ash, and metakaolin were observed to perform better than SF in terms of residual elasticity modulus of RAC. Overall, the modulus of elasticity of RAC decreases with an increasing proportion of mineral admixtures after 500 °C elevated temperature. Xie et al [39] further studied the effect of varying silica fume at low content between 0, 4, 8, and 12% on RAC modulus of elasticity. They found out that addition of silica fume in concrete mix presents a marginal variation after exposed temperature up till 200 °C and the highest modulus of elasticity is with 4% silica fume at 400 °C exposed temperature. They concluded that low content of silica fume can be beneficial to improve the compressive stiffness of RAC.

4. Influence of addition of fibers

4.1. Residual compressive strength

Researchers have investigated the effect of adding different fiber types on the compressive strength properties of concrete at elevated temperatures. This report focuses on the influence of steel, polypropylene, and hybrid (combination of steel and polypropylene) fibers. Eidan et al [29] considered temperature of 400 °C as the critical heating level for residual mechanical strength properties of fiber-reinforced concrete and found out that above heating level of 400 °C, the residual factors for fiber-reinforced concrete are generally higher than that of plain concrete. Steel fiber reinforced concrete (SFRC) with 1% addition performs better than non-SFRC for maximum exposure temperatures below 1000 °C; compressive strength loss is significantly slow down at higher temperatures [23]. A comparison between the effect of steel fiber and glass fiber on concrete strength at elevated temperature was investigated by Moghadam et al [57]. They observed that the compressive strength of normal, steel and glass fiber concrete drops as temperature rise to 100 °C because no chemical changes have occurred at this temperature range, however, above 100 °C, Steel fibers and Glass fiber concrete shows increased residual compressive strength in a range of 9 – 27 % and 1 – 18% respectively with 0.25% volume fraction each for steel and glass fiber at tested temperatures up to 800 °C. The improved residual compressive strength was attributed to the bonding properties of fibers with cement gel and the aggregates. On average, the normalized compressive strength of steel fiber reinforced concrete is higher than that of glass fiber by 12.95% at tested temperatures [57]. In general, the negative impact of increased temperature on the compressive performance of concrete is significantly counteracted by adding steel fiber, especially in high strength concrete containing silica fume [39].

The inclusion of Polypropylene (PP) fiber in concrete mix has also been observed to improve slightly the residual mechanical properties of concrete. The relative compressive strength of concretes containing PP fibers was higher than those of concretes without PP fibers while the addition of PP fibers was more effective for compressive strength compared to splitting tensile strength of concrete above 200 °C [44]. Eidan et al [29] also agree that

Polypropylene fiber-reinforced concrete exhibits higher residual mechanical strength compared to plain concrete. Their results showed that PP fibers neutralize the effect of physiochemical degradation of cement when the heating level is above 400 °C. The residual compressive strength of PP fiber-reinforced concrete with PP 12 mm length and 0.2% concrete volume dosage retained higher residual compressive strength of 25% of its initial strength while PP fiber-reinforced concrete with 6 mm length and plain concrete retained 21% and 12% respectively during exposure temperature range from 400 to 600 °C. They further noted that residual compressive strength of all fiber-reinforced mixes is lower than that of plain concrete mix below 300 °C, attributing this to the fact that the matrix was not affected by fiber until 300 °C temperature and pore pressure has not reached its critical level, whereas PP fibers have already melted and left microscopic channels within the matrix of fiber-reinforced concrete which eventually results in reduction in compressive strength. Both steel fiber and polypropylene fiber were both effective in minimizing the damaging effect of high temperatures on the compressive strength of concrete [94]. Similarly, addition of PP fiber at 0.45–1.8 kg/m^3 dosage shows little or no influence on the residual compressive strength of concrete subjected to high temperatures with retained residual compressive strength over 25% of room temperature value [95]. However, Poon et al [93] contradicted this claim and suggested that such differences might be derived from different test conditions or environments. This also agrees with Suhaendi & Horiguchi [77] observation. Although they acknowledged the significant mitigation mechanism with PP addition in terms of spalling occurrence especially in HSC due to melting of polypropylene fibers at 160–170 °C temperature, which provides passages for water vapor to escape thus reducing the pore pressure under heat exposition. Nevertheless, they concluded that residual properties of HSC reinforced by polypropylene fibers decreases due to intentionally generated additional pores in concrete.

The properties of concrete exposed to elevated temperature have been significantly improved by the addition of two separate fibers (Hybrid fibers) in concrete [94]. Especially, the addition of PP with other types of fibers such as steel and carbon fibers. Blend of steel and PP fiber performed better at elevated temperatures because the melting of PP fiber during the rapid temperature-increasing process creates microchannels that facilitate the release of the high vapor pressure due to inner moisture of concrete [43]. The residual strengths of hybrid fiber reinforced concretes were around 36% of their original strength at an elevated temperature of 800 °C. The understanding of the good synergy of steel and polypropylene fiber in concrete mix is further supported by results of [96,101] and [55]. Varona et al [55], observed that the NSC with hybrid fiber (PP and steel) gave better residual strength up to 650 °C than the NSC with only steel fibers. While plain NSC on the other hand shows lower residual compressive strength when compared to

Eurocode 2 and the Aslani & Bastami curve for calcareous NSC with no fiber content. They further observed that hybrid fiber (PP and Steel) concrete show higher residual compressive strength when compared Eurocode 2 standard, 0.3% volume fraction PP fiber concrete [96], and 0.5% volume fraction steel fiber HSC [38]. Nevertheless, the use of calcareous aggregates, which perform better than siliceous aggregates under high temperature is attributed as a possible reason for this improvement [55].

Overall, review of literature shows that steel fiber and hybrid fiber (PP & steel) significantly improve the residual compressive strength of concrete at high temperatures. They show slightly higher residual compressive strength than Eurocode 2 predictions for both calcareous and siliceous aggregate concrete. However, PP fiber slightly improves the residual compressive strength of concrete. Although the level of improvement falls below the Eurocode 2 values [18], they both show higher residual compressive strength compare to Aslani & Bastami curve for HSC predictions [79]. The statistical analysis of experimental data of residual compressive strength of HSC are performed and the regression lines obtained for each fiber types are presented in Fig. 13.

4.2. Residual tensile strength

It is well known that addition of fibers enhances the tensile strength of concrete and the increase can be up to 50% higher at room temperature [73,100]. Similarly, researchers have observed positive influence of fiber addition on concrete tensile strength at higher temperatures. Khaliq & Kodur [73] results showed that the addition of steel and hybrid fibers slows down the loss of tensile strength the most as temperature increase from 20 to 800 °C among the different types of high strength concrete considered (i.e fiber- reinforced concrete, self-consolidating concrete, and fly-ash concrete). The high melting temperature of steel fiber

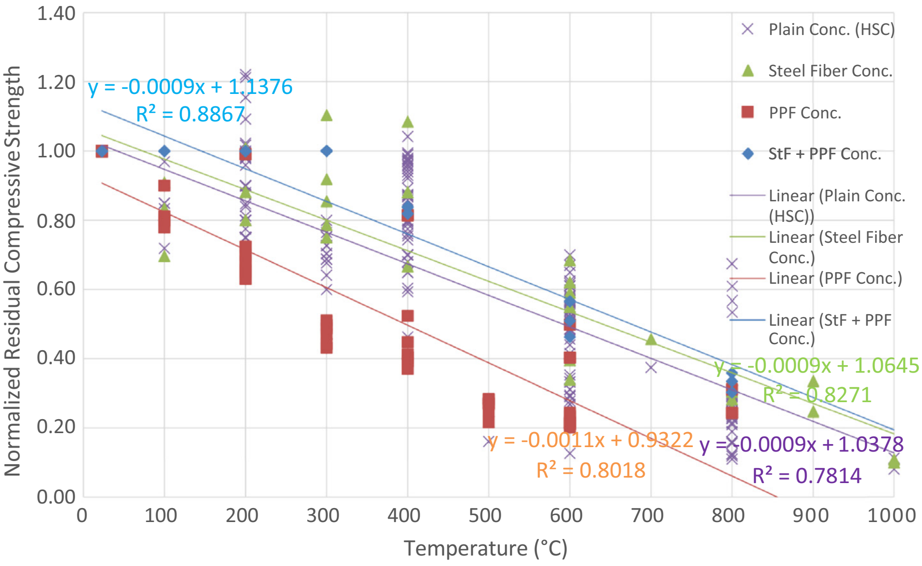


Fig. 13. Influence of Fibers on normalized residual compressive strength of High Strength Concrete.

allows it to retain its ductility and effectively resist failure under tension at high temperatures [43]. Khaliq & Waheed [35] noticed a positive high-temperature effect on splitting tensile strength of concrete up to 300 ℃, with an increase of 8% and 20% of room temperature strength at 120 ℃ and 300℃ respectively due to dry hardening, this is however followed by a sharp decrease at higher temperature levels. Generally, steel fibers are very effective to prevent cracking, hence, improve residual tensile strength. However, this influence was insignificant above 700 ℃ [35]. Furthermore, Moghadam et al [57] observed normal concrete tensile strength (30.3 MPa) at room temperature improved by 28.14% and 19.22% with addition of 0.25% volume fraction of steel and glass fiber respectively at room temperature. While during exposure to elevated temperature range 28 – 800 °C, steel fiber improves the tensile strength in a range of 8 – 198 %, and glass fiber improves tensile strength in the range of 19–213 %. Although, tensile strength loss occur as temperature rises due to incompatible expansion of aggregate and cement layers, and the formation of additional stresses inside the concrete. However, the rate of tensile strength reduction was significantly reduce in both steel and glass fiber concrete at elevated temperatures. This agrees with the findings of Gao et al [89] that the higher thermal conductivity of steel fiber compared to that of cement matrix and aggregates allows heat caused by thermal gradient to transmit more uniformly in steel fiber reinforced concrete, thus leading to lesser cracks and enhanced splitting tensile strength of concrete. 1.0% steel fiber content was indicated as the optimum amount in concrete in terms of relative splitting strength [89].

In the same way, a study on the influence of polypropylene fiber on concrete indicates its addition enhanced the residual splitting tensile strength of concrete. Eidan et al [29] observed polypropylene fiber reinforced concrete with 12 mm fiber length at dosage 0.2% volume fraction produced higher residual splitting tensile strength of approximately 27% of its initial strength after exposure to heating–cooling cycles. 400 °C was detected as the critical temperature level for residual mechanical strength (compressive, tensile, and modulus of elasticity) for PP fiber-reinforced concrete above which its residual factors are higher than that of plain concrete. Fibers' length of 12 mm produced better performance than 6 mm in high temperature [29]. On the contrary, [72] observed improved tensile strength of concrete at room temperature due to the presence of polypropylene fibers introduces additional closing pressure during crack growth that requires greater stresses in the matrix before critical crack propagation occurs. Nevertheless, no significant differences were observed in the relative splitting tensile strengths of concretes with and without PP fiber at high temperatures. In general, although, some standards such as Eurocode 2 consider residual tensile strength above 600 °C to be negligible, the addition of different type of fibers have shown significant retained tensile strength at and above this temperature level. Varona et al [55] results show a retained residual tensile strength around 15% at temperature above 800 °C with hybrid fiber reinforced concretes. The behavior of the residual tensile strength of concrete with fiber additions after elevated temperature as obtained from previous researches is show in Fig. 14 Fig. 15.

5. Stress-Strain behavior and modulus of elasticity

The addition of steel fiber in concrete influence its stress–strain response after exposure to elevated temperature generally based on compressive strength of concrete at room temperature and aggregate type used in the concrete mix. In the experimental work

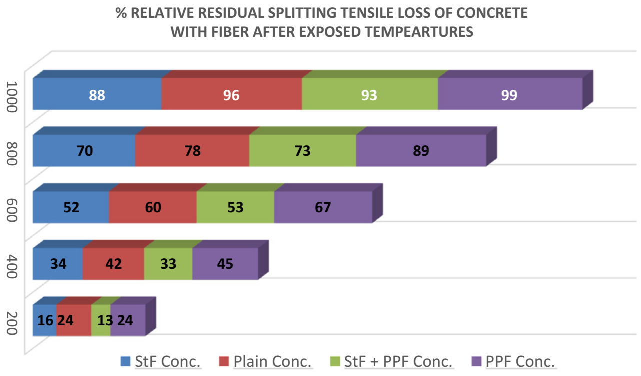


Fig. 15. Relative split tensile loss of concrete with fiber after exposed temperature.

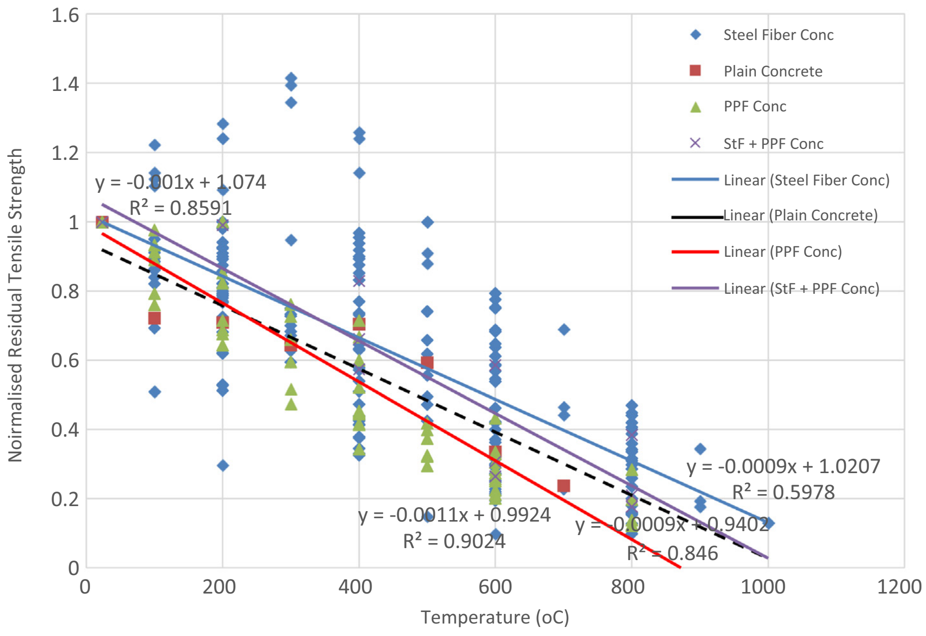


Fig. 14. The behavior of the residual tensile strength of concrete with fiber additions after elevated temperature.

by Chen et al [37], they varied steel fiber content of recycled aggregate concrete from 0.5%, 1.0%, and 1.5% volume content while comparing to control normal and recycled aggregate concrete specimens without fiber. They observed general reduction in the initial slope of the stress–strain curve as temperature increases resulting to increase in peak strain as temperature rises. The addition of large content of steel fiber in RAC resulted in higher strain; this is more obvious at higher exposure temperatures range from 400 °C and 600 °C. Similarly, Antonius et al [38] studied the effect of addition of 0.5% steel fiber on the residual properties of normal, medium, and high strength steel fiber concrete. There is degradation in the ductility of fiber along with an increase in temperature and compressive strength of concrete. For normal strength steel fiber concrete (NSFC), peak strain remains relatively unchanged with increased temperature, a gentler stress–strain curve was observed indicating the positive effect of steel fiber in improving the ductility of concrete at elevated temperatures. Whereas, the post-peak response in medium strength fiber concrete (MSFC) and high strength fiber concrete (HSFC) shows a significant decrease in ductility and peak strain after exposure to elevated temperature range 600 °C to 900 °C. The efficiency of steel fiber in maintaining concrete ductility at temperature range 600 °C to 900 °C is greatly reduced, hence both MSFC and HSFC behave like normal concrete without fiber (plain NSC) at this temperature range. They concluded that the proficiency level of ductility behavior of normal concrete has the highest quality and relatively increased despite the increased temperature. Similarly, Cheng et al [84] observed that increased strain in HSC with steel fiber, especially, at temperature range 600 – 800 °C indicating that HSC with steel fibers exhibits ductility better than HSC without fiber addition.

Most normal and high strength concrete mixes lost their elastic modulus up to 25% of that at room temperature until 400 °C heating cycle [27,37]. However, concrete with steel fiber addition has shown higher residual values of modulus of elasticity after exposed elevated temperatures [27,43]. Similarly, Xie et al [39] noticed that addition of steel fiber improves the temperature-dependent elastic modulus of recycled concrete, particularly, with a clearer margin after elevated temperature of 600 °C. Improved thermal conductivity of RAC resulting from more uniformly distributed internal thermal stress and less formation of crack after heating achieved through the addition of steel fiber was stated as the main reason for increase in elasticity modulus of RAC at elevated temperatures. This also agrees with the observation of Reddy and Pawade [97].

Previous researchers have studied the effect of polypropylene fiber on the modulus of elasticity of concrete. Pylia et al [98] reported nearly the same residual modulus of elasticity for concrete with and without PP fiber after elevated temperature of 600 °C. Similarly, Rudnik and Drzymała [99] focused on the PP fibers reinforced concrete behavior at elevated temperatures. They found out with addition of 1.8 kg/m^3 and 1.3 kg/m^3 of Monofilament 12-mm fibers and fibrillated 19-mm polypropylene fibers respectively, the influence on modulus of elasticity was not significantly pronounced for all observed elevated temperature range of 100 – 600 °C. Furthermore, the experimental work of Eiden et al [29] revealed that the addition of Polypropylene fiber does not contribute meaningfully to improving elastic modulus of concrete, and its effects completely vanish after concrete exposure to 600 °C elevated temperature.

5.1. Influence of aggregate type

5.1.1. Residual compressive strength

The impact of natural aggregate on concrete residual mechanical properties varies with their mineral composition. However, natural aggregates generally underperformed in terms of residual compressive strength when compared to recycled concrete aggregates, especially at higher elevated temperatures. From review, Tufail et al [33] noted that natural granitic aggregate concrete retained highest residual compressive strength at all test elevated temperatures up to 800 °C compared to natural limestone and quartzite. Likewise, Arioz [21] compared residual compressive strength of concrete made from natural crushed limestone and river gravel coarse aggregate during exposure temperature range 200 – 1200 °C. He observed a significant difference between the relative compressive strength in concrete with limestone (90%) and river gravel (50%) of unheated concrete strength after exposed temperature to 600 °C. while at 1200 °C, crushed limestone and river gravel aggregate strength decreases to 6% and 0% of their unheated strength. The lower relative strength in river gravel aggregate was attributed to its composition of siliceous mineral that expands the most at elevated temperature [100]. A different range of natural aggregates such as crushed granite, limestone, quartzite, and siliceous river gravel, in which crushed granite are reported to yield higher residual strength followed by quartzite, limestone, and river gravel, respectively.

On the other hand, other experimental data showed that recycled aggregates concrete present lower damage levels from heat and higher relative residual compressive strength properties when compared to natural aggregates generally during exposure to high temperatures [53]. This has been attributed to the fact that recycled aggregate-cement phase is composed of mortal, hence, similar level of coefficient of thermal expansion between recycled aggregates and new cement mortal paste leads to fewer cracks formation at elevated temperatures, which leads to improved residual compressive strength [14,48]. Sarhat & Sherwood [48] found out that increasing the replacement level of RCA resulted in improved residual compressive strength. The improvement is more significant at elevated temperatures above 500 °C and was attributed to a better match of thermal expansion properties between recycled aggregate and cement paste. They concluded that recycled aggregate concrete has higher residual compressive strength compared to natural river gravel and crushed limestone concrete at observed elevated temperature and that 75% replacement ratio gave the highest ratio of residual to initial compressive strength, which makes it the optimal replacement level. Similarly, Xiao et al [49] noted that while residual compressive strength of normal concrete decreases drastically at temperature greater than 300 °C, that of RAC shows a rise when elevated temperature is above 300 °C. Furthermore, replacement percentage of 50% and above present higher residual compressive strength compared to normal concrete and 30% replacement level. Salahuddin et al [56] observed a reduced residual compressive strength for 100% RCA at initial temperature of 200 °C, but ultimately, after elevated temperature of 600 °C, experience slight improvement in the compressive strength compared to the control mix of natural aggregates. This improvement is attributed to the increased amount of recycled mortar adhered with the recycled aggregates, subsequently enhancing the thermal expansion properties among the aggregates and cement paste. The same positive influence of RCA was observed in high strength concrete by Khaliq [53]. The rate of drop in compressive strength was lower for RA-HSC compared to that of NA-HSC due to its porous microstructure that allowed easy moisture or vapour movement, resulting in less physical deterioration (thermal cracking) and damage under high- temperature exposure.

Few researchers observed opposing views. The results of Gale et al [51] indicated that residual strength of natural limestone concrete replaced with coarse RCA at 0%, 30%, and 100% presents a proportional decrease in retained compressive strength value as RCA content increases when tested after exposure to 500 °C temperature. The mechanical performance of RAC diminished at elevated temperature much more than conventional concrete. This was attributed to weak interface between the old cement on RCA and the new cement-inter- facial transition zone (ITZ), weaker strength of RCA at high temperature, micro-cracking possibly induced during sourcing, fabrication and previous stress history during its service life. However, He noted that the reduction in 100% RCA concrete still meets the characteristic strength reduction guidance of Eurocode 2 [18] with less than 25% strength reduction for calcareous and 40% for siliceous. This also agrees with the observation of Chen et al [37] that the residual compressive strength of 100% RCA concrete during 20 – 600 °C exposure suffers faster decrease in compressive strength than NA concrete. Viera et al. [46] however concluded that residual compressive strength of 100% RCA concrete compared to NA concrete is approximately the same at each thermal exposure temperature level up to 800 °C. Fig. 16 compares the response of NA and RCA normalized residual compressive strength after exposure to elevated temperature Fig. 17.

Coarse recycled concrete aggregates in concrete mix have been studied extensively in literature. However, limited studies are available for fine recycled concrete aggregates in terms of its influence on the residual mechanical properties of concrete at elevated temperatures. Results obtained by Wang et al [27] showed that fine RCA content had significant influence on the concrete compressive strength when subjected to high temperature. Concrete with 50% fine recycled aggregate showed higher residual

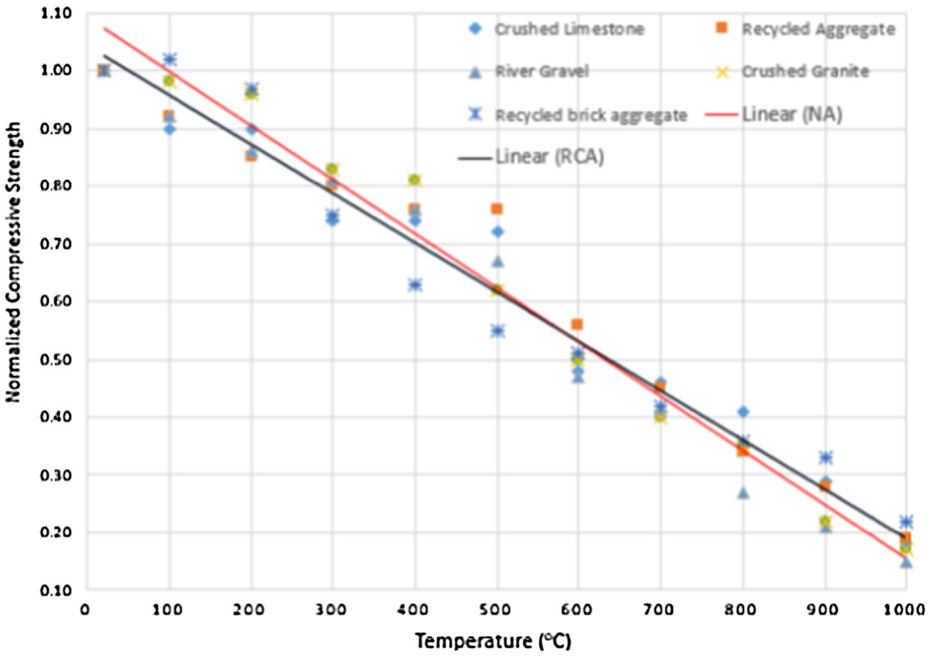


Fig. 16. Behaviour of natural and recycled aggregate concrete residual compressive strength after elevated temperature (*data from:* [9,21,23,27,33,36,37,31,51,54,55,49,40,41,42,46,48,88,57]).

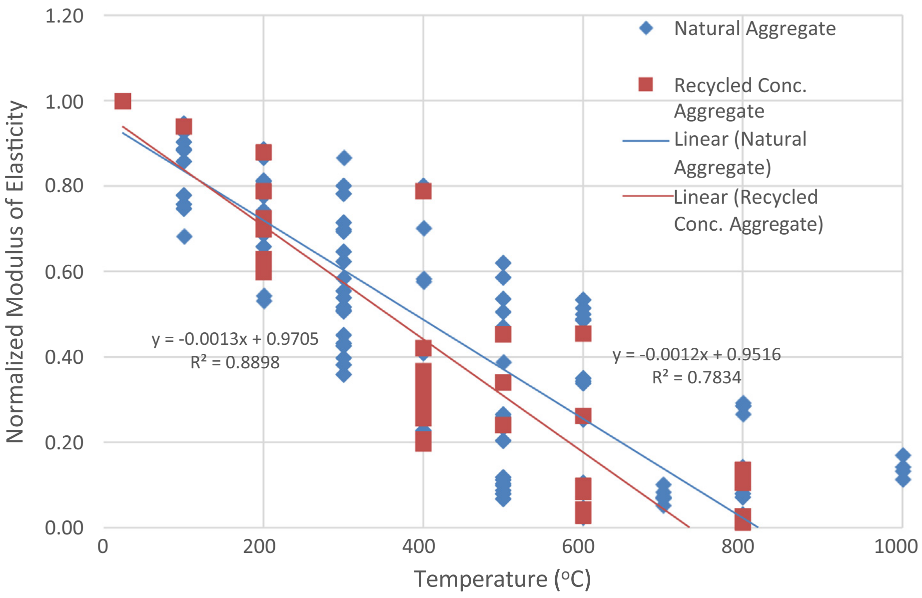


Fig. 17. Normalized modulus of elasticity of natural and recycled aggregates at exposed temperature.

compressive strength compared to natural river sand aggregate and 100% fine recycled aggregate. However, In terms of normalized residual strength, 100% fine RCA content present higher value than those with 0% and 50% up to 800 °C. The positive influence of fine RCA on the normalized residual compressive strength was attributed to similar thermal expansion properties of fine RCA and new concrete cement mortar.

5.1.2. Residual tensile strength

Similar to compressive strength, the type of mineral composition of natural aggregates influences the residual tensile properties at ambient and elevated temperatures. The residual tensile strength of natural granitic concrete is 195% and 186% higher than that of limestone and quartzite concrete respectively at elevated temperature of 650 °C [33]. Comparing natural aggregate to recycled concrete aggregates, studies [82,100,101] observed recycled aggregate concrete suffers greater tensile strength loss due to presence of non-cementitious impurities that burns and melted at high temperature thereby creating voids and imperfections in concrete, and also as a result of higher number of interfaces in recycled concretes which enhances the development of cracks. Likewise, a thermal insulation concrete produce from recycled aggregate by Liu et al [102] showed a significant decrease in residual tensile strength after exposed temperature up to 800 °C, the residual tensile strength deterioration increases with increase RCA percentage and more, when compared to that observed in compression. On the contrary, Sarhat and Sherwood [48] investigated the residual tensile strength of recycled aggregate. They found out that increasing the replacement of RCA level resulted in improved residual tensile strength. Salahuddin et al [56] also found out that concrete mixtures with 30% replacement of recycled aggregates exhibited almost 35% higher splitting tensile strength as compared to the natural aggregates control mix at room temperature. However, they did not investigate their performance at elevated temperatures. RCA aggregates can be seen to perform weaker in terms of residual split tensile strength at initial temperature, however, improvement in its tensile strength properties becomes noticeable at temperature range 400 – 600 °C.

Recycled fine aggregate has been observed to influence the residual tensile strength properties of concrete Liang Jiong-Feng [103], and Rafi and Aziz[104] results showed that the residual mechanical strength properties of concrete specimens containing recycled fine aggregate including compressive strength, splitting tensile strength, elastic modulus is lower than that of natural aggregates. Whereas, Wang et al [27]'s study on the influence of fine recycled aggregate at elevated temperature, concluded that fine recycled concrete aggregates content had no regular influence on the normalized residual splitting tensile strength after exposure to high temperature, considering the level of fluctuation between recycled fine aggregate content and corresponding concrete normalized residual splitting tensile strength and relatively low value of tensile strength at elevated temperatures.

5.1.3. Stress–strain behavior and modulus of elasticity

The stress–strain relationship of normal concrete produced with three different natural aggregates was investigated by Tufail et al [33]. They observed that the ultimate compressive strain of natural aggregate (normal) concrete varies from one another, depending on the aggregate type and exposed temperature level. Among the three groups of natural aggregates tested, quartzite concrete had the highest compressive strain above 200 °C followed by limestone and granite. The peak strain of concrete generally increases with rise in temperature, indicating increased ductility of normal concrete at elevated temperature [51]. For recycled aggregate concrete, Kien et al [54] observed that the slope of ascending branch of stress–strain curve of RAC was much lower than that of normal concrete after exposed 500 °C temperature, indicating larger deformability (strain) in the ascending branch of the curve. Also, the critical strain of RAC subjected to the elevated temperature was 8.44% higher than that of NAC. Higher porosity and lower density due to presence of attached mortal were highlighted as the main reasons for higher critical strain in recycled aggregate concrete. Xie et al [39] observed an overall decrease in peak stress with total replacement of natural aggregate with recycled aggregate, recycled aggregate has higher water absorption rate, hence, loss of free water at elevated temperature created larger void in recycled concrete after heating and cooling cycle. The larger void ratio in recycled concrete is attributed as the main reason for decreased peak stress in RAC. Furthermore, the stress–strain response of HSC from natural and recycled aggregate was the focus of Khaliq [53] laboratory experimental work. Studies have reported that both concrete types experience decrease in ultimate peak stress and an increase in the corresponding peak strain as temperature rises. The large increase in the strains particularly above 400 °C temperatures is attributed to factors including the following: physical and chemical changes in concrete, microstructural deterioration, initiation and propagation of microcracks, calcination of carbonates, and disintegration of calcium silicate hydrates (C-S-H) [102,105–110]. The peak residual strain in RA-HSC is consistently higher than that of NA-HSC and the margin becomes more obvious with increase in temperature indicating that relative performance of RA-HSC is better than that of NA-HSC at temperatures above 400 °C.

The characteristics of aggregate type in concrete mix significantly affect the modulus of elasticity of concrete. Many researchers have observed that the contribution of compressive strength of concrete to variation in modulus of elasticity is less significant compare to the influence of different aggregate type in concrete mix, especially at ambient temperature [37,39]. Zega & Maio [9] found out that at the same w/c ratio, the static modulus of elasticity obtained in recycled aggregate concrete is lower by 13% compared to that of normal concrete at room temperature due to attached mortar that induced significant changes in RAC deformability properties. However, after exposure to 500 °C temperature, they found out that the rate of decrease in modulus of elasticity in RAC is less that of normal concrete due to similar coefficient of thermal expansion between recycled aggregate mortar and fresh mortar at the interface zone leading to less effect of high temperature and better behavior of RAC interface zone. Some researchers have however observed differently. Gales and Cree [51] observed considerable variability between measured modulus of elasticity for concrete mix of natural and recycled aggregates after exposed temperatures compared to their values at ambient temperature. Unlike at ambient temperature, where changes in modulus of elasticity become more obvious with increase in RCA content, no clear trends or obvious differences were noticed for modulus of elasticity at high temperatures with increase in RCA content. Furthermore, Khaliq [53] observed that the trends in the loss of elastic modulus with increasing temperature are similar in normal and recycled aggregate high strength concrete. Although NA-HSC has a slightly higher room temperature elastic modulus compared to that of RA-HSC. These results are in general agreement with [46,48,54] where a consistently lower residual modulus of elasticity of recycled aggregate concrete compared to that of natural aggregate concrete at all elevated temperatures were observed but with similar rate of reduction of elastic modulus. This reduction has been mainly attributed to the presence of old attached mortar in RCA, which produce a RAC with higher deformability compared to NAC [105]. Tufail et al [33] investigation focused on the modulus of elasticity of normal concrete produced from three different natural aggregate types (granite, quartzite, and limestone) at room temperature. Granite has the highest elastic modulus at 38.2 GPa compared to that of quartzite (31.2 GPa) and limestone (23.0 GPa). The same trend was maintained after elevated temperatures with granite concrete still maintaining highest modulus of elasticity.

6. Research needs

- There is general acceptability of GGBS improvement on concrete mechanical properties at room temperature. However, limited research work studied its influence on residual properties of concrete at elevated temperatures. There is need for more experimental research work to better understand GGBS' influence on concrete exposed to high temperature.
- There should be the inclusion of ternary mixtures of supplementary cementitious materials to fully comprehend the synergistic effects of different SCMs when combined in the mix of concrete exposed to high temperature.
- Fibers or its hybrid have been reported to improve residual properties of concrete. Carbon and glass fiber shows good prospect in terms of positively enhancing residual compressive and tensile strength properties, however, limited works are observed in this area, hence the need for more experimental research work in other to understand better the behavior of concrete mix with these fibers separately or its hybrid with well understand fiber like steel fiber.
- Most reported work has adopted standard concrete mix design approach in the estimation of concrete mix constituent materials irrespective of aggregate type (natural or recycled). There is need to investigate the possible influence of different mix design approaches on concrete residual properties to develop a novel concrete mix design that will significantly contribute to enhancing concrete residual properties.

7. Conclusion

This study covered a review of residual strength properties of normal and high strength concrete exposed elevated temperatures: the implication of natural and recycled aggregates, the addition of mineral admixtures, and fibre. The following conclusions were drawn from the study:

-The heat generated from fire causes high-temperature gradient in concrete that initiates chemical and physical reactions such as dehydration of cement paste, decomposition of aggregates, mass loss, deformation, and mechanical strength loss.

- Normal strength concrete may experience an increase in compressive strength at initial elevated temperature due to dry hardening and formation of heating steam with internal autoclave condition causing further hydration of cement paste in concrete. Concrete generally starts to experience reduction in residual compressive strength at elevated temperature due to changes in hydrothermal conditions from loss of free and absorbed water, development of microcracks and internal stress from thermal expansion of aggregates above 300 °C.
- The splitting tensile strength of concrete is more sensitive to high temperatures than compressive strength. It decreases with increasing temperature because of the decomposition of C-A-S-H gel, reduction of chemically bonded water, and loosening of compactness of mortal.
- HSC is affected at elevated temperatures more than NSC, with a higher rate of degradation and strength. The addition of SCM and Fibers improves the residual compressive strength of both NSC and HSC at elevated temperatures.
- Recycled concrete aggregates concrete retained higher residual mechanical strength properties in terms of compressive and tensile strength at higher elevated temperatures, but losses its modulus of elasticity faster at elevated temperature. RCA concrete has less deterioration at elevated temperature due to its porous nature that allows easy moisture or vapour movement and a better match of the coefficient of thermal expansion between attached mortal on recycled aggregates and new cement paste.
- FA and GGBS significantly mitigate deterioration and reduced concrete compressive and tensile strength loss in concrete at elevated temperature because of further hydration reaction of the reactive powders of FA and GGBS that is accelerated under high temperature. FA and GGBS show higher improved residual compressive strength compare to silica fume and Nano silica. However, excessive FA and GGBFS content reduces the residual mechanical strength properties of concrete
- Silica fume performs poorly in terms of compressive strength and shows higher strength loss compare to plain concrete at elevated temperatures. The ultra-fine particles of SF cause denser transition zone between aggregates and paste which hinders easy escape of moisture causing internal pore pressure and cracks development.
- The blend of nano-silica (nS) with Silica fume performed better in residual mechanical properties than when each mineral admixture is used separately. The changes in the microstructure of concrete with nano-silica shows the tendency for relative residual compressive strength to decrease with its increasing content.
- Steel fiber significantly slows down compressive and tensile strength loss at higher temperatures. The high melting temperature of steel fiber provides the capacity to retain its ductility and effectively resist failure under tension at elevated temperatures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P.J.G.R.A. Smith, R.R. Kersey, The construction industry mass balance: Resource use, wastes and emissions The Construction Industry Mass Balance: Resource use, wastes and emissions, Viridis Rep. VR4 (Revised), CIRIA. 4 (2003) 1–105.
[2] N.K. Sharma, P. Kumar, S. Kumar, B.S. Thomas, R.C. Gupta, Properties of concrete containing polished granite waste as partial substitution of coarse aggregate, Constr. Build. Mater. 151 (2017) 158–163.
[3] M.S. Imbabi, C. Carrigan, S. Mckenna, Trends and developments in green cement and concrete technology, Int. J. Sustain. Built Environ. 1 (2013) 194–216, https://doi.org/10.1016/j.ijsbe.2013.05.001.
[4] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review, Constr. Build. Mater. 68 (2014) 501–516.
[5] V. Kodur, Properties of concrete at elevated temperatures, ISRN Civ. Eng. 2014 (2014).
[6] H. Mostafaei, Hybrid fire testing for performance evaluation of structures in fire-part 1: methodology, Natl. Res. Counc. Canada. (2011) 22.
[7] L. Zhu, J. Dai, G. Bai, F. Zhang, Study on thermal properties of recycled aggregate concrete and recycled concrete blocks, Constr. Build. Mater. 94 (2015) 620–628.
[8] Q. Ma, R. Guo, Z. Zhao, Z. Lin, K. He, Mechanical properties of concrete at high temperature — A review, Constr. Build. Mater. 93 (2015) 371–383, https://doi.org/10.1016/j.conbuildmat.2015.05.131.
[9] C.J. Zega, A.A. Di Maio, Recycled concrete exposed to high temperatures, 9831 (2006) 675–682.
[10] S. Ni, T. Gernay, Predicting residual deformations in a reinforced concrete building structure after a fire event, Eng. Struct. 202 (2020), https://doi.org/10.1016/j.engstruct.2019.109853.
[11] V.K.R. Kodur, N.K. Raut, X.Y. Mao, W. Khaliq, Simplified approach for evaluating residual strength of fire-exposed reinforced concrete columns, Mater. Struct. 46 (2013) 2059–2075.

[12] S. Lim, Effects of Elevated Temperature Exposure on Cement- Based Composite Materials, 2015.

[13] J.M. de Burgh, S.J. Foster, Influence of temperature on water vapour sorption isotherms and kinetics of hardened cement paste and concrete, Cem. Concr. Res. 92 (2017) 37–55, https://doi.org/10.1016/j.cemconres.2016.11.006.

[14] C.J. Zega, A. Antonio, D. Maio, Recycled concrete made with different natural coarse aggregates exposed to high temperature, Constr. Build. Mater. 23 (2009) 2047–2052, https://doi.org/10.1016/j.conbuildmat.2008.08.017.

[15] P.O. Awoyera, C. Arum, I.I. Akinwumi, Significance of concrete cover to reinforcement in structural element at varying temperatures, Int. J. Sci. Eng. Res. 5 (2014) 1120–1123.

[16] Y. Guo, J. Zhang, G. Chen, Z. Xie, Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures, J. Clean. Prod. 72 (2014) 193–203.

[17] ACI Committee 216, ACI 216R-90 Guide for determining the fire endurance of concrete elements, Concr. Int. 3, 1994, 13–47.

[18] The European Union, EN 1992-1-2 (2004): Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design, 2004.

[19] ASCE, Structural Fire Protection American Society of Civil Engineers, ASCE Manuals and Reports on Engineering Practise No. 78, American Society of Civil Engineers, 1992.

[20] ASTM E119, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, ASTM Int. West Conshohocken, PA. 552 (2016). https://doi.org/10.1520/E0119-14.

[21] O. Arioz, Effects of elevated temperatures on properties of concrete, 42 (2007) 516–522. https://doi.org/10.1016/j.firesaf.2007.01.003.

[22] T. Rilem, 129-MHT, Test methods for mechanical properties of concrete at high temperatures, Part 4—tensile strength for service and accident conditions, Mater. Struct. 33 (2000) 219–223.

[23] A. Lau, M. Anson, Effect of high temperatures on high performance steel fibre reinforced concrete, Cem. Concr. Res. 36 (2006) 1698–1707, https://doi.org/10.1016/j.cemconres.2006.03.024.

[24] Q. Ren, Y. Wu, X. Zhang, Y. Wang, Effects of fly ash on the mechanical and impact properties of recycled aggregate concrete after exposure to high temperature, Eur. J. Environ. Civ. Eng. (2019) 1–17, https://doi.org/10.1080/19648189.2019.1677505.

[25] O. Arioz, Retained properties of concrete exposed to high temperatures: Size effect, Fire Mater. (2009) 211–222, https://doi.org/10.1002/fam.

[26] D. Rajawat, S. Siddique, S. Shrivastava, S. Chaudhary, T. Gupta, Influence of fine ceramic aggregates on the residual properties of concrete subjected to elevated temperature, Fire Mater. 42 (2018) 834–842, https://doi.org/10.1002/fam.2639.

[27] Y. Wang, F. Liu, L. Xu, H. Zhao, Effect of elevated temperatures and cooling methods on strength of concrete made with coarse and fine recycled concrete aggregates, Constr. Build. Mater. 210 (2019), https://doi.org/10.1016/j.conbuildmat.2019.03.215.

[28] M. Bastami, M. Baghbadrani, F. Aslani, Performance of nano-Silica modified high strength concrete at elevated temperatures, Constr. Build. Mater. 68 (2014) 402–408, https://doi.org/10.1016/j.conbuildmat.2014.06.026.

[29] J. Eidan, I. Rasoolan, A. Rezaeian, D. Poorveis, Residual mechanical properties of polypropylene fiber-reinforced concrete after heating, Constr. Build. Mater. 198 (2019) 195–206, https://doi.org/10.1016/j.conbuildmat.2018.11.209.

[30] L.T. Phan, Fire Performance of High-Strength Concrete: A Report of the state of the Art, 1996.

[31] S. Ahmad, Y.S. Sallam, M.A. Al-Hawas, Effects of key factors on compressive and tensile strengths of concrete exposed to elevated temperatures, Arab. J. Sci. Eng. 39 (2014) 4507–4513, https://doi.org/10.1007/s13369-014-1166-8.

[32] X. Hou, M. Abid, W. Zheng, G.Q. Waqar, Evaluation of residual mechanical properties of steel fiber-reinforced reactive powder concrete after exposure to high temperature using nondestructive testing, Procedia Eng. 210 (2017) 588–596, https://doi.org/10.1016/j.proeng.2017.11.118.

[33] M. Tufail, K. Shahzada, B. Gencturk, J. Wei, Effect of elevated temperature on mechanical properties of limestone, quartzite and granite concrete, Int. J. Concr. Struct. Mater. 11 (2017) 17–28, https://doi.org/10.1007/s40069-016-0175-2.

[34] W. Khaliq, V. Kodur, High temperature mechanical properties of high-strength fly ash concrete with and without fibers, ACI Mater. J. 109 (2012).

[35] W. Khaliq, F. Waheed, Mechanical response and spalling sensitivity of air entrained high-strength concrete at elevated temperatures, Constr. Build. Mater. 150 (2017) 747–757, https://doi.org/10.1016/j.conbuildmat.2017.06.039.

[36] W. Yonggui, L. Shuaipeng, P. Hughes, F. Yuhui, Mechanical properties and microstructure of basalt fibre and nano-silica reinforced recycled concrete after exposure to elevated temperatures, Constr. Build. Mater. 247 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118561 118561.

[37] G.M. Chen, Y.H. He, H. Yang, J.F. Chen, Y.C. Guo, Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures, 71 (2014) 1–15. https://doi.org/10.1016/j.conbuildmat.2014.08.012.

[38] Antonius, A. Widhianto, D. Darmayadi, G.D. Asfari, Fire resistance of normal and high strength concrete with contains of steel fibre, 15 (2014) 655–669.

[39] J. Xie, Z. Zhang, Z. Lu, M. Sun, Coupling effects of silica fume and steel-fiber on the compressive behaviour of recycled aggregate concrete after exposure to elevated temperature, Constr. Build. Mater. 184 (2018).

[40] Y. Xu, Y.L. Wong, C.S. Poon, M. Anson, Impact of high temperature on PFA concrete, Cem. Concr. Res. 31 (2001) 1065–1073.

[41] C.S. Poon, S. Azhar, M. Anson, Y.L. Wong, Comparison of the strength and durability performance of normal- and high-strength pozzolanic concretes at elevated temperatures, Cem. Concr. Res. 31 (2001) 1291–1300, https://doi.org/10.1016/S0008-8846(01)00580-4.

[42] C.S. Poon, S. Azhar, M. Anson, Y.L. Wong, Performance of metakaolin concrete at elevated temperatures, Cem. Concr. Compos. 25 (2003) 83–89, https://doi.org/10.1016/S0958- 9465(01)00061-0.

[43] B. Chen, J. Liu, Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures, 34 (2004) 1065–1069. https://doi.org/10.1016/j.cemconres.2003.11.010.

[44] A. Behnood, H. Ziari, Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures, Cem. Concr. Res. 30 (2008) 106–112, https://doi.org/10.1016/j.cemconcomp.2007.06.003.

[45] M. Ghandehari, A. Behnood, M. Khanzadi, Residual mechanical properties of high-strength concretes, Asce. (2010) 59–64.

[46] J.P.B. Vieira, J.R. Correia, J. De Brito, Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates, Cem. Concr. Res. 41 (2011) 533–541, https://doi.org/10.1016/j.cemconres.2011.02.002.

[47] I. Netinger, I. Kesegic, I. Guljas, The effect of high temperatures on the mechanical properties of concrete made with different types of aggregates, Fire Saf. J. 46 (2011) 425–430, https://doi.org/10.1016/j.firesaf.2011.07.002.

[48] S.R. Sarhat, E.G. Sherwood, Residual mechanical response of recycled aggregate concrete after exposure to elevated temperatures, J. Mater. Civ. Eng. 25 (2013) 1721–1730, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000719.

[49] J. Xiao, Y. Fan, M.M. Tawana, Residual compressive and flexural strength of a recycled aggregate concrete following elevated temperatures, Struct. Concr. 14 (2013) 168–175, https://doi.org/10.1002/suco.201200037.

[50] M.S. Khan, H. Abbas, Effect of elevated temperature on the behavior of high volume fly ash, Concrete 00 (2014) 1–7, https://doi.org/10.1007/s12205-014-1092-z.

[51] J. Gales, D. Cree, Fire Performance of Sustainable Recycled Concrete Aggregates: Mechanical Properties at Elevated Temperatures and Current Research Needs, (2015). https://doi.org/10.1007/s10694-015-0504-z.

[52] K. Rekha, M. Potharaju, Residual Compressive Strength of Recycled Brick Aggregate Concrete at High Temperatures, 5 (2015) 159–164.

[53] W. Khaliq, Mechanical and physical response of recycled aggregates high-strength concrete at elevated temperatures, Fire Saf. J. 96 (2018) 203–214, https://doi.org/10.1016/j.firesaf.2018.01.009.

[54] N. Kien, T. Satomi, H. Takahashi, Effect of mineral admixtures on properties of recycled aggregate concrete at high temperature, Constr. Build. Mater. 184 (2018) 361–373, https://doi.org/10.1016/j.conbuildmat.2018.06.237.

[55] F.B. Varona, F.J. Baeza, D. Bru, S. Ivorra, Influence of high temperature on the mechanical properties of hybrid fibre reinforced normal and high strength concrete, Constr. Build. Mater. 159 (2018) 73–82, https://doi.org/10.1016/j.conbuildmat.2017.10.129.

[56] H. Salahuddin, A. Nawaz, A. Maqsoom, T. Mehmood, B. ul A. Zeeshan, Effects of elevated temperature on performance of recycled coarse aggregate concrete, Constr. Build. Mater. 202 (2019) 415–425. https://doi.org/10.1016/j.conbuildmat.2019.01.011.

[57] M.A. Moghadam, R.A. Izadifard, Effects of steel and glass fibers on mechanical and durability properties of concrete exposed to high temperatures, Fire Saf. J. (2020), https://doi.org/10.1016/j.firesaf.2020.102978 102978.

[58] P.K. Mehta, P.J.M. MONTEIRO, Concrete: Microstructure, properties and materials., New York, 2006, Phys. Prop. Sieve Size Accord. to Iraqi Stand. (n. d.) 90–100.

[59] H. Dilbas, M. Şimşek, Ö. Çakır, An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume, Constr. Build. Mater. 61 (2014) 50–59.

[60] H.W. Iqbal, R.A. Khushnood, W. Latif Baloch, A. Nawaz, R.F. Tufail, Influence of graphite nano/micro platelets on the residual performance of high strength concrete exposed to elevated temperature, Constr. Build. Mater. 253 (2020), https://doi.org/10.1016/j.conbuildmat.2020.119029 119029.

[61] H. Zhao, F. Liu, H. Yang, Residual compressive response of concrete produced with both coarse and fine recycled concrete aggregates after thermal exposure, Constr. Build. Mater. 244 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118397.

[62] Y.S. Tai, H.H. Pan, Y.N. Kung, Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800°c, Nucl. Eng. Des. 241 (2011) 2416–2424, https://doi.org/10.1016/j.nucengdes.2011.04.008.

[63] M. Abid, X. Hou, W. Zheng, R.R. Hussain, High temperature and residual properties of reactive powder concrete – A review, Constr. Build. Mater. 147 (2017) 339–351, https://doi.org/10.1016/j.conbuildmat.2017.04.083.

[64] M. Alexander, A. Bentur, S. Mindess, Durability of concrete: design and construction, CRC Press, 2017.

[65] J. Xiao, G. König, Study on concrete at high temperature in China - An overview, Fire Saf. J. 39 (2004) 89–103, https://doi.org/10.1016/S0379-7112(03)00093-6.

[66] K. Behfarnia, M. Shahbaz, The effect of elevated temperature on the residual tensile strength and physical properties of the alkali-activated slag concrete, J. Build. Eng. 20 (2018) 442–454, https://doi.org/10.1016/j.jobe.2018.08.015.

[67] V. Afroughsabet, T. Ozbakkaloglu, Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers, Constr. Build. Mater. 94 (2015) 73–82.

[68] F. Hasan-Nattaj, M. Nematzadeh, The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica, Constr. Build. Mater. 137 (2017) 557–572.

[69] Y-F. Chang, Y-H. Chen, M-S. Sheu, G.C. Yao, Residual stress–strain relationship for concrete after exposure to high temperatures, Cem. Concr. Res. 36 (2006) 1999–2005.

[70] A.M. Neville, J.J. Brooks, Concrete technology, Longman Scientific & Technical England (1987).

[71] M. Ghandehari, A. Behnood, M. Khanzadi, Residual mechanical properties of high-strength concretes after exposure to elevated temperatures, J. Mater. Civ. Eng. 22 (2010) 59–64.

[72] A. Behnood, M. Ghandehari, Comparison of compressive and splitting tensile strength of high- strength concrete with and without polypropylene fibers heated to high temperatures, Fire Saf. J. 44 (2009) 1015–1022, https://doi.org/10.1016/j.firesaf.2009.07.001.

[73] W. Khaliq, V.K.R. Kodur, Effect of high temperature on tensile strength of different types of high-strength concrete, ACI Mater. J. 108 (2011).

[74] V.K.R. Kodur, L. Phan, Critical factors governing the fire performance of high strength concrete systems, Fire Saf. J. 42 (2007) 482–488, https://doi.org/10.1016/j.firesaf.2006.10.006.

[75] G. Choe, G. Kim, N. Gucunski, S. Lee, Evaluation of the mechanical properties of 200 MPa ultra- high-strength concrete at elevated temperatures and residual strength of column, Constr. Build. Mater. 86 (2015) 159–168, https://doi.org/10.1016/j.conbuildmat.2015.03.074.

[76] F. Aslani, M. Bastami, Constitutive relationships for normal-and high-strength concrete at elevated temperatures, ACI Mater. J. 108 (2011) 355.

[77] S.L. Suhaendi, T. Horiguchi, Effect of short fibers on residual permeability and mechanical properties of hybrid fibre reinforced high strength concrete after heat exposition, Cem. Concr. Res. 36 (2006) 1672–1678, https://doi.org/10.1016/j.cemconres.2006.05.006.

[78] L.T. Phan, J.R. Lawson, F.L. Davis, Effects of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete, Mater. Struct. 34 (2001) 83–91.

[79] F. Aslani, M. Bastami, Constitutive Relationships for Normal- and High-Strength, (2011) 355–364.

[80] M. Heikal, H. El-Didamony, T.M. Sokkary, I.A. Ahmed, Behavior of composite cement pastes containing microsilica and fly ash at elevated temperature, Constr. Build. Mater. 38 (2013) 1180–1190, https://doi.org/10.1016/j.conbuildmat.2012.09.069.

[81] Y.N. Chan, G.F. Peng, M. Anson, Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures, 21 (1999) 23–27.

[82] C. Laneyrie, A.L. Beaucour, M.F. Green, R.L. Hebert, B. Ledesert, A. Noumowe, Influence of recycled coarse aggregates on normal and high performance concrete subjected to elevated temperatures, Constr. Build. Mater. 111 (2016) 368–378. https://doi.org/10.1016/j.conbuildmat.2016.02.056.

[83] Y.W. Lee, G.Y. Kim, N. Gucunski, G.C. Choe, M.H. Yoon, Thermal strain behavior and strength degradation of ultra-high-strength-concrete, Mater. Struct. 49 (2016) 3411–3421, https://doi.org/10.1617/s11527-015-0728-x.

[84] F.P. Cheng, V.K.R. Kodur, T.C. Wang, Stress-strain curves for high strength concrete at elevated temperatures, J. Mater. Civ. Eng. 16 (2004) 84–90, https://doi.org/10.1061/(ASCE)0899- 1561(2004)16:1(84).

[85] M.S. Khan, H. Abbas, Effect of elevated temperature on the behavior of high volume fly ash concrete, KSCE J. Civ. Eng. 19 (2014) 1825–1831.

[86] W. Li, Z. Luo, Z. Tao, W.H. Duan, S.P. Shah, Mechanical behavior of recycled aggregate concrete-filled steel tube stub columns after exposure to elevated temperatures, Constr. Build. Mater. 146 (2017) 571–581.

[87] G. Li, X. Zhao, Properties of concrete incorporating fly ash and ground granulated blast-furnace slag, Cem. Concr. Compos. 25 (2003) 293–299.

[88] D.H. Reddy, A. Ramaswamy, Influence of mineral admixtures and aggregates on properties of different concretes under high temperature conditions I : Experimental study, J. Build. Eng. (2017), https://doi.org/10.1016/j.jobe.2017.09.013.

[89] D. Gao, D. Yan, X. Li, Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures, Fire Saf. J. 54 (2012) 67–73, https://doi.org/10.1016/j.firesaf.2012.07.009.

[90] D. Shen, Y. Jiao, J. Kang, Z. Feng, Y. Shen, Influence of ground granulated blast furnace slag on early-age cracking potential of internally cured high performance concrete, Constr. Build. Mater. 233 (2020), https://doi.org/10.1016/j.conbuildmat.2019.117083 117083.

[91] S.C. Kou, C.S. Poon, M. Etxeberria, Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures, Cem. Concr. Compos. 53 (2014) 73–82, https://doi.org/10.1016/j.cemconcomp.2014.06.001.

[92] G. Mathew, M.M. Paul, Influence of fly Ash and GGBFS in laterized concrete exposed to elevated temperatures, J. Mater. Civ. Eng. 26 (2014) 411–419, https://doi.org/10.1061/(ASCE)MT.1943- 5533.0000830.

[93] C.S. Poon, Z.H. Shui, L. Lam, Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures, Cem. Concr. Res. 34 (2004) 2215–2222, https://doi.org/10.1016/j.cemconres.2004.02.011.

[94] L. Dong, XJ; Ding, YN; Cao, Effects of fibers on mechanical properties of high-performance concrete subjected to elevated temperatures, J. Harbin Inst. Technol. (2008) 8.

[95] Y. Kim, T. Lee, G. Kim, An experimental study on the residual mechanical properties of fiber reinforced concrete with high temperature and load, Mater. Struct. (2013) 607–620, https://doi.org/10.1617/s11527-012-9918-y.

[96] G.F. Peng, S.H. Bian, Z.Q. Guo, J. Zhao, X.L. Peng, Y.C. Jiang, Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures, Constr. Build. Mater. 22 (2008) 948–955, https://doi.org/10.1016/j.conbuildmat.2006.12.002.

[97] D.V. Reddy, P.Y. Pawade, Combine Effect of Silica Fume and Steel Fiber on Mechanical Properties on Standard Grade of, (2012).

[98] P. Pliya, A. Beaucour, A. Noumowé, Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature, Constr. Build. Mater. 25 (2011) 1926–1934, https://doi.org/10.1016/j.conbuildmat.2010.11.064.

[99] E. Rudnik, Thermal behavior of polypropylene fiber-reinforced concrete at elevated temperatures, J. Therm. Anal. Calorim. 131 (2018) 1005–1015, https://doi.org/10.1007/s10973-017-6600-1.

[100] Y. Anderberg, S. Thelandersson, A constitutive law for concrete at transient high temperature conditions, Spec. Pub. 55 (1978) 187–206.

[101] Rafi MM, Aziz T, Lodi S. Residual Properties of Concrete Exposed to Elevated Temperatures. Proceedings of the Institution of Civil Engineers – Structures and Buildings 2020; 173(9):655-671.

[102] Y. Liu, H. Ji, J. Zhang, W. Wang, Y.F. Chen, Mechanical properties of thermal insulation concrete with recycled coarse aggregates after elevated temperature exposure, Mater. Test. 58 (2016) 669–677.

[103] W.E. LiangJiong-Feng, L.-L. ZhouXu, Influence of high temperature on mechanical properties of concrete containing recycled fine aggregate, Comput. Concr. 21 (2018) 87–94.

[104] M.M. Rafi, T. Aziz, Experimental testing of fly ash containing recycled aggregate concrete exposed to high temperatures, Sustain. Resilient Infrastruct. (2019), https://doi.org/10.1080/23789689.2019.1681820.

[105] L.T. Phan, High strength concrete at high temperature, Am. Concr. Institute, ACI Spec. Publ. (2002) 1–22.

[106] W. Khaliq, Performance characterization of high performance concretes under fire conditions, 2012.

[107] D. Xuan, B. Zhan, C.S. Poon, Thermal and residual mechanical profile of recycled aggregate concrete prepared with carbonated concrete aggregates after exposure to elevated temperatures, Fire Mater. 42 (2018) 134–142, https://doi.org/10.1002/fam.2465.

[108] R. Felicetti, P.G. Gambarova, Effects of high temperature on the residual compressive strength of high strength silicious concretes, ACI Mater. J. 95 (4) (1998) 395–406.

[109] Thelandersson S. (1972), ‘‘Effect of High Temperatures on Tensile Strength of Concrete”. Division of Structural Mechanics and Concrete Construction, Bulletin 26, Lund Institute of technology, Lund, Swedon.

[110] Adam M. Knaack, Yahya C. Kurama, and David J. Kirkner (2009). Stress-Strain Properties of Concrete at Elevated Temperatures (Report #NDSE-09-01). Structural Engineering Research Report, University of Notre Dame, USA.