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Properties and Behavior of Geopolymer Concrete Subjected to Explosive Air Blast Loading: A Review

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Abstract. The severe damage to civilian buildings, public area, jet aircraft impact and defense target under explosive blast loading can cause a huge property loss. Most of researcher discusses the topics on design the concrete material model to sustain againts the explosive detonation. The implementation of modern reinforcement steels and fibres in ordinary Portland cement (OPC) concrete matrix can reduce the extreme loading effects. However, most researchers have proved that geopolymer concrete (GPC) has better mechanical properties towards high performance concrete, compared to OPC. GPC has the high early compressive strength and high ability to resist the thermal energy from explosive detonation. In addition, OPC production is less environmental friendly than geopolymer cement. Geopolymer used can lead to environmental protection besides being improved in mechanical properties. Thus, this paper highlighted on an experimental, numerical and the analytical studies cause of the explosive detonation impact to concrete structures.

1 Introduction

Geopolymer is an alternative material as to replace the used of ordinary Portland cement (OPC). The side effect of using OPC is increasing the percentage of carbon dioxide release in the air surrounding. Nowadays, geopolymer concrete is widely used in constructing buildings namely as beam, slab, girder, column and wall. These main structures must be mechanically design to withstand high loads and external impact. Researchers have reported geopolymer concrete is higher compressive strength and can resist temperature up to 800 ^{o}C [1, 2]. The significant finding is that the use of sodium silicate as alkaline activator increases the compressive strength, potentially due to the high concentration of silica and alumina [3]. The existing of silica to form geopolymer chains is compulsory for strong bonds within the

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polymer chain, generating subsequently a hardened structure [4]. The strength of GPC is also caused by the nature of geopolymer concrete that is self-compacting, avoid creating air traps as well as eliminating pour inside while curing [5, 6].

Most of the previous researches, explosive blasting only discussed on OPC concrete instead of geopolymer concrete. Many researchers have been exploring the reinforcing and mixing addition, such as steel, fiber, carbon and nylon into the concrete mold [7-11]. Recent developed concrete materials enhanced mechanical properties and durability to strengthen itself [12]. As known, concrete has a brittle properties materials. Then, the testing under blast loads was conducted to ensure the reliability of concrete structure to be proof against blast [13]. Limiting the damage concrete structures also aggressively design to protect the civilian buildings in a war or terrorist attack area [14].

An explosive detonation was conducted on air blast, blast in confined space [15] and, consequently, direct contact with blast load [9, 16]. Blast in confined space will trigger more energy concentration while the pressure behavior in air blast is low frequency blast vibration. It is because air overpressure waves radiate outward to the air surrounding then lower the energy waves concentration [17]. The extreme energy from detonation can create impulsive impact and in consequence, many researchers proposed the high strength of the concrete structures [12-15, 26]. Therefore, this paper reviews on the geopolymer concrete performance towards explosive blast loading.

2 Experimental model on blast events.

In the past studies, most of the experimental set up on concrete blasting was conducted through air blast conditions [8, 18, 19]. The critical considered parameter in experimental before setting up the blast events are standoff distance, mass of explosive, types of explosive and concrete model material. Figure 1 shows the experimental setup from previous study which is investigating on deformation of reinforced concrete (RC) beams under blast [20].

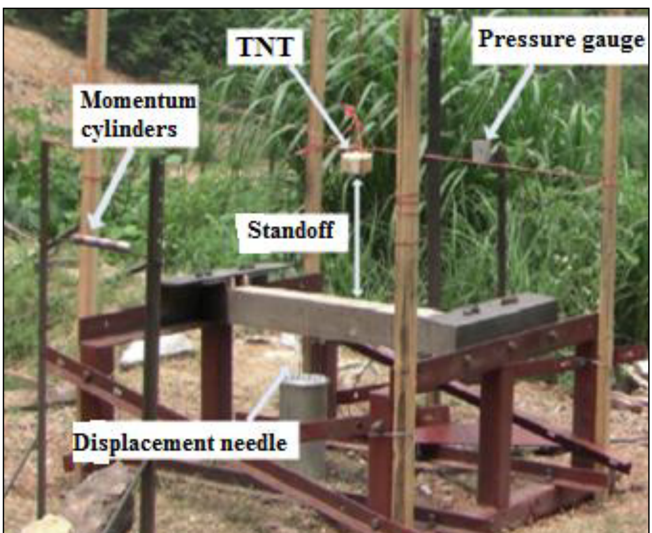

Fig. 1. Test set up for air blast loading [20]

Furthermore, a pressure sensor transducer also locates by other researcher to measure the pressure exerted from the blast. Then, the amount of energy from the explosion hit the concrete beam can be obtained by using the pressure sensor. The maximum deflection and residual deflection are computed through the measurement Linear Variable Differential Transformer (LVDT) [21, 22].

3 Explosive selections

Velocity of detonation (VOD) and density of explosives was differed through their physical state as solids, liquids or gases [23]. Solids explosive cause more damage after explosion. The detonation of solid explosives may give rise shock wave under pressure up to 30000 MPa and temperatures about 3000- 40000C [14]. The types of secondary solid explosives that is trinitrotoluene (TNT) [24-26] and ammonium nitrate/ fuel oil (ANFO) [11] mostly used in concrete blast events.

The commercial explosive also been used in blast experiment, although the velocity of detonation is fewer than TNT and ANFO. Table 1 shows the different type of Emulex explosive as commercial explosive in the industry according to its capability effect.

Table 1. Types of Emulex as commercial explosive [27]

Emulex Explosive	Application	Velocity of detonation (m/s)	Density (g cm^{-3})
Emulex® 100 (Pipe Charge for Pre-Splitting)	For general surface blasting. Intended for column charging and priming. Without aluminum powder.	4500	1.05 - 1.15
Emulex® 150 (Surface & Underwater Blasting)	Specialised in surface and underwater blasting. Use as both column and bottom charge. Added with aluminum to provide higher explosive energy.	4,500 - 5,400	1.12 - 1.24
Emulex® 180 (underground/tu nnelling blasting	Formulated for underground blasting and tunneling needs. Intended for column charging or priming. Posses superb explosion energy to enhance pull factor.	4,500- 5,700	1.10 - 1.25

4 Standoff Distance

Theoretically, the standoff distance may vary according to material use for blasting as refer to Unified Facilities Criteria-DoD Minimum Antiterrorism Standards for Bulidings, UFC 4-010-01,31 July 2002 [28]. The mass of explosive is directly proportional to standoff distance. There are a research that performed a blast test with 0.51kg mass of TNT with 400mm standoff distance, 34kg and 1675mm [11], respectively. Some researcher also conducted an experiment that evaluate the level of performance of reinforce concrete slab by varying the explosive weight and standoff distance [29]. The effective distance can be obtained by calculating using the formula [8] as below:

$$Z = R/\sqrt[3]{W} , \tag{1}$$

where R is the standoff distance and W is the mass of explosive.

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5 Materials and structural element types

Concrete is a brittle construction materials. It can provide effective resistance to fire and shock wave during blast. The high resistance also provided by reinforced concrete structures which are important in structure close to explosion sources. There are several types of fiber reinforcement use in concrete enhancing strength as shown in Table 2. Commonly, the main role of fiber reinforcement imparts more resistant to impact loading, thus, increase ductility and reduce permeability of concrete elements [30].

Table 2. Classification of fibres [4]

Types of Fiber	Descriptions
Steel Fiber	Different shapes and dimensions, also microfibres
Glass Fiber	In cement matrices used only as alkali-resistant (AR) fibres
Synthetic Fiber	Fibres made with different materials: polypropylene, polyethylene and polyolefin, polyvinyl alcohol (PVA)
Carbon Fiber	Pitch and polyacrylonitrile (PAN) fibres

A previous research conducted a tests on six 2.74 m x 0.2 m x 0.2 m simply supported RC beams with two 16 mm diameter rebars. The results show that the fibre reinforced beam has high effectiveness in increasing the blast resistance compared to non-fibre reinforcement [31]. Moreover, research has been carried out for improving the blast resistance by employing fibre reinforced concrete. The result of blast test is shown in Table 3 was computed on crack width, length of deflection and mass loss in percentage for different reinforcement. The studies indicated that the variation of the reinforcement provided a different level of damage and performance.

Table 3. Performance of reinforced concrete after blast detonations [32]

Specimen (Ø 10)	Crack width	Deflection (mm)	Mass loss (%)
Steel bars reinforced concrete	16	82	30
Fibre reinforced concrete (FRC)	NA	NA	50
FRC + steel bars	2	5	0
Reinforced concrete (Glass fibre reinforced polymer bars)	2	9	5
RC (steel bars) + GFRP laminate	3	8	8

6 Numerical analysis of concrete structures

6.1 Pressure behaviour during explosion

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The tremendous energy from explosive detonation generates higher heat stress and shock pressure wave in the atmosphere. Figure 2 shows the pressure behaviour for air blast. Before the shock wave reach, the atmospheric pressure, P_a at t_A, then fluctuate until the peak pressure, P_{so} after explosion. The pressure drop to P_a at $t_A + t_D$, next achieve $P_{so'}$, the negative pressure peak before return again at atmospheric pressure [14].

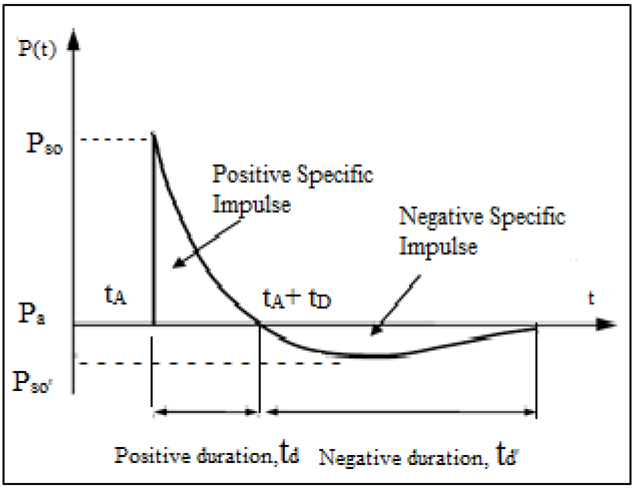

Fig. 2. Air blast pressure- time profile [14]

Theoretically, it is very inconsistent to determine the air blast pressure wave, depending on the environment condition. Due to that, Baker proposed equation to express the pressure as simplify the process [33].

$$P_{so}(t) = P_{so}\left(1 - \frac{t}{t_0}\right)e^{\frac{-t}{t_0}} \tag{2}$$

where t is duration of the pressure wave travel to the given location, t_o is the time from peak pressure to atmospheric pressure. The impulse generates by positive pressure also can be obtained using its integral to time.

$$I_{so} = \int_{t_a}^{t_a + t_o} P_{so}(t)dt \tag{3}$$

A researcher proposed the empirical equations for shock wave calculation by collecting data from experimental and numerical [34].

$$P_{so} = 1.4072Z^{-1} + 0.554Z^{-2} - 0.0357Z^{-3} + 0.000625Z^{-4}\ (0.1 \le Z \le 0.3)$$
$$P_{so} = 0.619Z^{-1} - 0.033Z^{-2} + 0.213Z^{-3}\ (0.3 \le Z \le 1)$$
$$P_{so} = 0.066Z^{-1} - 0.405Z^{-2} + 0.329Z^{-3}\ (1 \le Z \le 10) \tag{4}$$

where Z is the scaled distance,expressed by $Z = \frac{R}{\sqrt[3]{W}}$, R is the standoff distance and W is the mass of explosive.

6.2 Strain-rate effect

The strain rate effect is very critical factors for a concrete structural response. Concrete dynamic behaviour also influenced the strain rate effect. The Dynamic Increase Factor (DIF), Compressive Dynamic Increase Factor (CDIF) and Tensile Dynamic Increase Factor (TDIF) empirical equations [35] have been suggested to calculate the effect on tensile and compressive strength.
For concrete compression,

$$\text{CDIF} = \frac{f_c}{f_{cs}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{cs}}\right)^{1.206\,\alpha} \text{ for } \dot{\varepsilon} \leq 30\text{s}^{-1}$$

$$\text{CDIF} = \frac{f_c}{f_{cs}} = \gamma_s\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{cs}}\right)^{\frac{1}{3}} \text{ for } \dot{\varepsilon} > 30\text{s}^{-1} \tag{5}$$

where f_c is the dynamic compressive strength at strain rate $\dot{\varepsilon}$, f_{cs} is the static compressive strength at $\dot{\varepsilon}_{cs}$; $\log \gamma$= 6.156α- 0.49; α=1/ (5 + 3$f_{cu}/4$) and f_{cu} is the static cube compressive strength in MPa.

For concrete tension,

$$\text{TDIF} = \frac{f_t}{f_{ts}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ts}}\right)^{\delta} \text{ for } \dot{\varepsilon}_{td} \leq 1\text{s}^{-1}$$

$$\text{TDIF} = \frac{f_c}{f_{ts}} = \beta = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ts}}\right)^{\frac{1}{3}} \text{ for } \dot{\varepsilon}_{td} > 1\text{s}^{-1} \tag{6}$$

where f_t is the dynamic tensile strength at strain rate $\dot{\varepsilon}$ in the range of 10^{-6} to 160 s^{-1}, f_{ts} is the static tensile strength at $\dot{\varepsilon}_{ts}$; $\log \beta$= 6δ- 2 ; δ=1/ (1 + 8f'_c/f'_{co}); f'_c is the static uniaxial compressive strength of concrete and f'_{co} is taken as 10MPa.

While the DIF relationship for steel reinforcement formulated as below[36].

$$\text{DIF} = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha} \text{, take as } \alpha = 0.074 - 0.040 f_y / 414 \tag{7}$$

where f_y is steel yield strength in MPa.

6.3 Analytical approach for explosive blasting

An analytical analysis are performing by using the computer simulation software to illustrate the real and programming of explosive detonation. Typically, researcher carried out the simulation on explosive blasting using computer program is summarize in Table 4.

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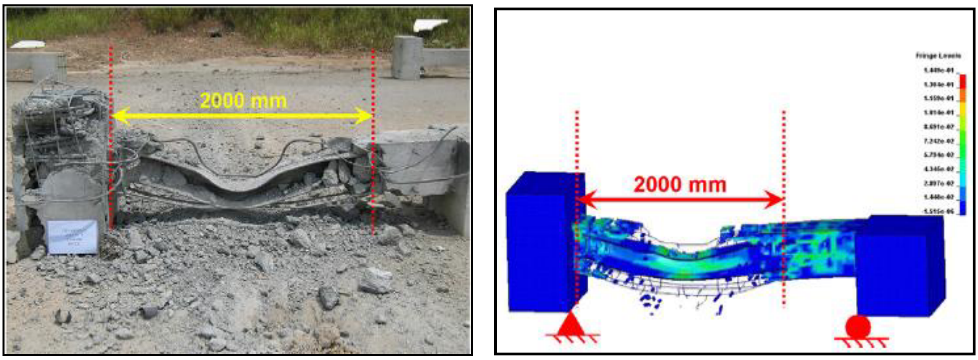
Table 4. List of computer software for blast simulation [14]

Software	Ability	Author/Vendor
LS-DYNA	Structural response+ CFD (Couple analysis)	Livermore Software Technology Corporation (LSTC)
BLASTX	Blast prediction, CFD code	SAIC
CTH	Blast prediction, CFD code	Sandia National Laboratories
FEFLO	Blast prediction, CFD code	SAIC
FOIL	Blast prediction, CFD code	Applied Research Associates, Waterways Experiment Station
SHARC	Blast prediction, CFD code	Applied Research Associates,Inc
DYNA3D	Structural response+ CFD (Couple analysis)	Lawrence Livermore National Laboratory (LLNL)
ALE3D	Couple analysis	Lawrence Livermore National Laboratory (LLNL)
Air3D	Blast prediction, CFD code	Royal Military of Science College, Cranfield University
CONWEP	Blast prediction (empirical)	US Army Waterways Experiment Station
AUTODYN	Structural response+ CFD (Couple analysis)	Century Dynamics
ABAQUS	Structural response+ CFD (Couple analysis)	ABAQUS Inc

From the past study, the test result of concrete damage after blasting are consulted by using LS DYNA and the accuracy of the analytical model is provided by comparing the results on analytical and experimental as shown in Figure 3.



(a) (b)

Fig. 3. Comparison of damage between experimental (a) and analytical (b)[16]

Based on the studies have been done, LS-DYNA and AUTODYN commonly used as it is commercial numerical hyrocodes [18, 24, 25, 37]. A 2D finite element model was simulated by using LS-DYNA for modelling fiber reinforcement concrete and predict the observed damage [8]. Next, the numerical simulation of the dynamic response and residual axial capacity of composite columns was also investigated by using LS-DYNA [9]. While, the previous researcher studied using LS-DYNA to simulate the prestressed reinforced concrete beam under blast loads [11]. In contrast, according to the past research, AUTODYN was suggested to simulate the blast wave propagation in 2D simulation [37].

7 Summary

Design consideration in concrete withstands the shock wave from the explosion is very important. Hence, it can minimize and reduce the risk and damage impact from the detonation. Definitely, public buildings and defense area may lead to safety as to prevent attack from terrorist or war. Therefore, the design of high strength concrete may result in high cost consumption, in the meantime, it can be decrease by using the geopolymer concrete as well as reduce pollution problems.

References

1. I.H. Aziz, M.M. Al Bakri Abdullah, H. Cheng Yong, L. Yun Ming, K. Hussin, E.A. Azimi, Key Eng. Mat., **34** (2015)
2. H.y. Zhang, V. Kodur, L. Cao, S.l. Qi, Procedia Eng. **71**, 153 (2014)
3. L.N. Assi, E. Deaver, M.K. ElBatanouny, P. Ziehl, Constr. Build. Mater. **112**, 807 (2016)
4. O.A. Abdulkareem, M. Ramli, Modern Applied Science, **9**, 61 (2015)
5. E. Arioz, O. Arioz, O.M. Kockar, Procedia Eng., **42**, 100 (2012)
6. H.Y. Zhang, V. Kodur, S.L. Qi, L. Cao, B. Wu, Constr. Build. Mater., **55**, 38 (2014)
7. P.A. Buchan, J.F. Chen, Woodhead Publishing, 269 (2010)
8. S.j. Yao, D. Zhang, F.y. Lu, W. Wang, X.g. Chen, Eng. Fail. Anal., **62**, 103 (2016)
9. A.M. Coughlin, E.S. Musselman, A.J. Schokker, D.G. Linzell, Int. J. Impact Eng., **37**, 521 (2010)
10. D. Kakogiannis, F. Pascualena, B. Reymen, L. Pyl, J. M. Ndambi, E. Segers, Fire Safety J., **57**, 69 (2013)
11. Z.S. Tabatabaei, J.S. Volz, J. Baird, B.P. Gliha, D.I. Keener, Int. J. Impact Eng., **57**, 70 (2013)
12. A.M. Brandt, Compos. Struct., **86**, 3 (2008)
13. M.A. Yusof, N. Mohamad Nor, A. Ismail, N. Choy Peng, R. Mohd Sohaimi, M.A. Yahya, Adv. Mater. Sci. Eng., **2013**, **(**2013)
14. T. Ngo, P. Mendis, A. Gupta, J. Ramsay, Electronic Journal of Structural Engineering **7**, 76 (2007)
15. C.F. Zhao, J.Y. Chen, Y. Wang, S.J. Lu, Theor. Appl. Fract. Mec., **61**, 12 (2012)
16. K.C. Wu, B. Li, K.C. Tsai, J. Constr. Steel. Res., **67**, 602 (2011)
17. C. Wu, M. Lukaszewicz, K. Schebella, L. Antanovskii, J. Loss. Prevent. Proc., **26**, 737 (2013)
18. W. Chen, H. Hao, S. Chen, Mater. Des., **65**, 662 (2015)
19. X. Lin, Y.X. Zhang, P.J. Hazell, Mater, Desi, **56**, 620 (2014)
20. B. Yan, F. Liu, D. Song, Z. Jiang, Eng. Fail. Anal., **51**, 9 (2015)
21. J. Li, C. Wu, H. Hao, Mater. Des, **82**, 64 (2015)
22. G. Carta, F. Stochino, Eng. Struct., **49**, 306 (2013)
23. J. P. Agrawal, *High energy materials: propellants, explosives and pyrotechnics* (John Wiley & Sons, 2010)

24 G. Thiagarajan, A.V. Kadambi, S. Robert, C.F. Johnson, Int. J. Impact. Eng. **75**, 162 (2015)
25. L. Chernin, M. Vilnay, I. Shufrin, Int. J. Mech. Sci., **106**, 331 (2016)
26. Y. Shi, M.G. Stewart, Struct. Saf., **53**, 13 (2015)
27. Z.X. Zhang, *Explosives and Detonators," in Rock Fracture and Blasting* (Butterworth-Heinemann, 179, 2016)
28. J.P. Hanus, R.W. Welch, *Applying UFC 4-010-01 in Baghdad, Iraq* (Structures Congress 2005@ sMetropolis and Beyond, 1, 2005)
29. P.F. Silva, B. Lu, Compos. Part B-Eng., **38**, 523 (2007)
30. P.A. Buchan, J. F. Chen, Compos. Part B-Eng., **38**, 509 (2007)
31. C.A. Ross, M. Purcell, E.L. Jerome, Building to Last, 673 (1997)
32. C.P. Pantelides, T.T. Garfield, W.D. Richins, T.K. Larson, J.E. Blakeley, Eng. Struct. **76**, 24 (2014)
33. W.E. Baker, *Explosions in air* (University of Texas Press, 1973)
34. J. Henrych, R. Major, *The dynamics of explosion and its use* (Elsevier Amsterdam, 1979)
35. Y. Shi, M.G. Stewart, Int. J. Impact Eng., **85**, 5 (2015)
36. L.J. Malvar, Aci Mater J -American Concrete Institute, **95**, 609 (1998)
37. X. Q. Zhou, V. A. Kuznetsov, H. Hao, J. Waschl, Int. J. Impact Eng., **35**, 1186 (2008)